
Protective Current and Voltage Relays

10.1 What are “Protective Relays”

What are “current relays” and “voltage relays” and what is the difference between them?

These relays are specially designed for current or voltage level control in electric circuits of high and low voltage, and for generation of certain output signals, when the current or voltage level deviates from a preassigned value. Such relays are also called “measuring relays,” since in the process of operation they constantly measure the level of the actuating value. Very often the output signal of such relays affects the power shutdown device, de-energizing the load and thus protecting it (or the main supply) from damages in emergency modes, which is why such relays are also called “protective relays.”

Some relays of this type have powerful contacts directly switched to the protected circuit, or a powerful electromagnet mechanically linked with the power shutdown device. Such relays are called “direct-action” relays (Figure 10.1a). Low-power relays, which only give control signals to an independent power-switching device (a circuit breaker, for example), are called “indirect-action” relays (Figure 10.1b). In the above examples the relays are connected directly to the controlled current circuit. Such relays are called “primary” ones. As a rule, coils of primary current and voltage relays are designed for currents not exceeding 50 to 200 A, and for voltages of not more than 400 V.

10.2 Current and Voltage Transformers

And what should be done when one needs to control currents of hundreds and thousands of amperes, or very high voltages? In this case the relays are connected not directly to the strong current or high-voltage circuit but through special matching transformers called “current transformers” (CT) and “voltage transformers” (VTs). Relays connected to the controlled circuit through such intermediate transformers are called “secondary” ones (Figure 10.2).

What are CTs and VTs? Like any transformer, a low-voltage CT consists of a primary winding designed for the current in the controlled circuit, a secondary winding to which relays and measuring devices are connected, and also a laminated steel core (Figure 10.3a). Sometimes there is no primary winding in a CT, and the transformer itself looks like a toroid (Figure 10.3b). In this case copper wire or the bus bar is used as a primary winding (it is considered to contain one turn). The primary currents of CT can reach tens of thousands amperes. Standard values for secondary currents are 5 or 1 A. It is for these

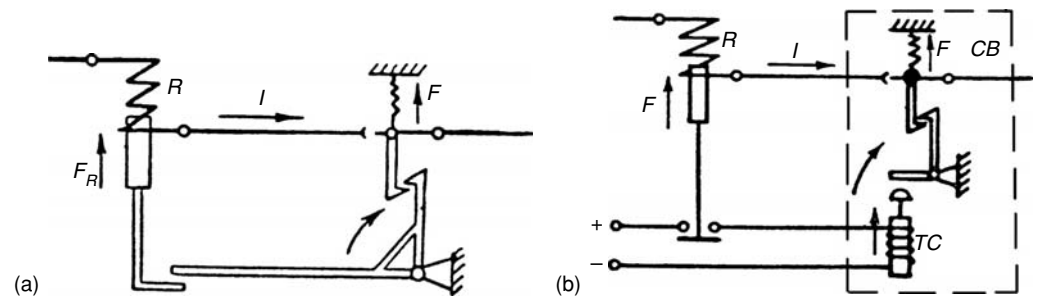


FIGURE 10.1
A schematic plot illustrating the principle of application of primary relays, “direct-acting” (a) and “indirect-acting” (b). R — relay; TC — trip coil; CB — circuit breaker.

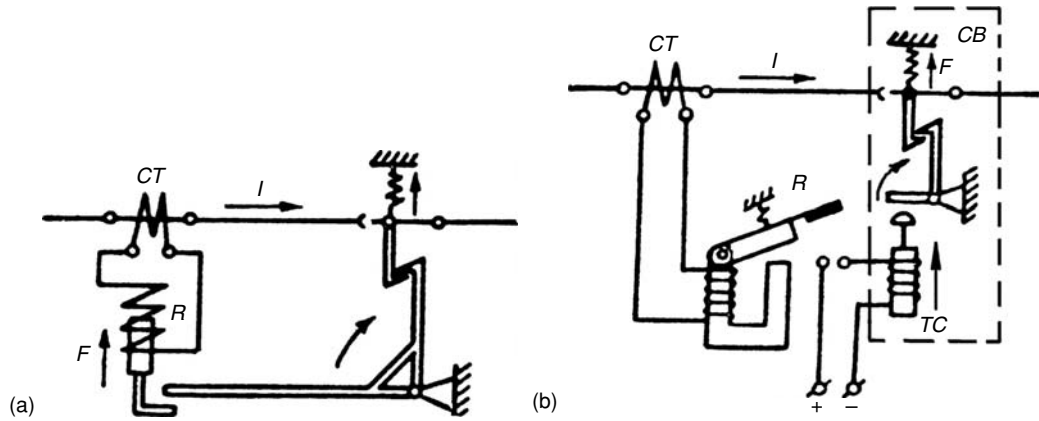


FIGURE 10.2
A schematic plot illustrating the principle of application of secondary relays, “direct-acting” (a) and “indirect-acting” (b). CT — current transformer.

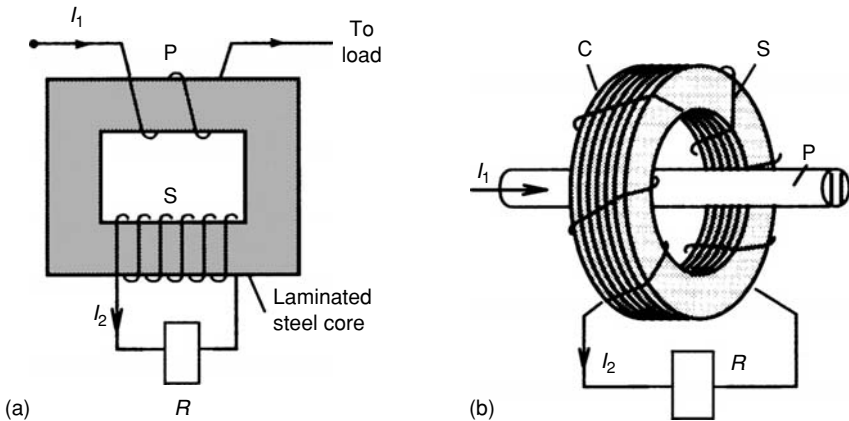
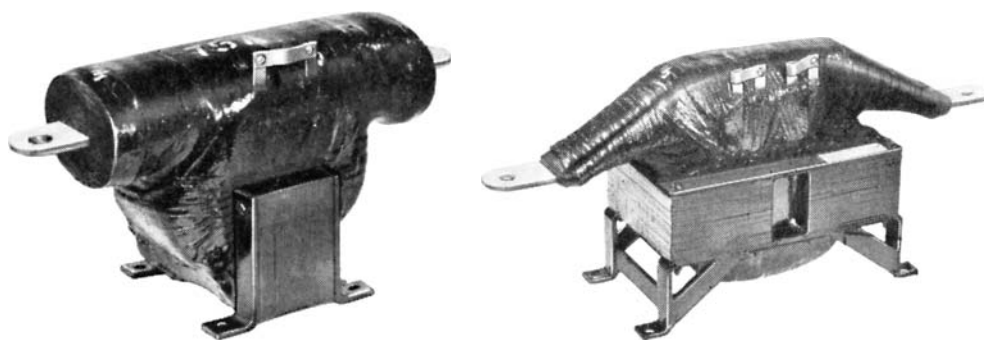


FIGURE 10.3
Principle of construction of CTs. P — primary winding; S — secondary winding; C — laminated steel core; R — relay.

**FIGURE 10.4**

JS-1 type CTs for internal installation of the 15 kV class, with insulation in the form of cloth tapes impregnated with asphalt-base insulating compound (General Electric Instruction GEC-333B 1955).

current values that most relays in the world are constructed today. The ratio of the primary current (voltage) to the secondary current (voltage) is called the transformer ratio. As a rule, in the CT there is a layer of insulating material between the windings and the core. Transformers designed for operation under high voltages are insulated with particular care. Earlier transformers for middle-class voltages (6 to 36 kV) used to be insulated with the help of special cloth tapes impregnated with a so-called asphalt-base insulating compound, after having been wound around (Figure 10.4).

As it can be seen from Figure 10.4, it was only the piece of bus bar used as a primary winding that was insulated. The magnetic core in such construction was not insulated. After assembly, the whole transformer together with the magnetic core was covered with black varnish (based on a similar asphalt-based insulating compound). Such transformers did not look aesthetically beautiful.

Modern CTs of such class are molded with a special high-quality epoxy resin after assemblage, at the factory. The molding process is carried out with vacuum and increased pressure cycling, thus providing full impregnation of all CT elements and preventing the formation of air bubbles inside both the transformer and the magnetic core. The process results in quite aesthetic solid constructions (Figure 10.5a).

Recently are more and more widely applied CTs with the split core (Figure 10.5b). Such transformers are convenient for mounting and dismounting. After installation of two half of core and connection among themselves, they strongly snuggle up to each other. Magnetic properties of such core do not differ almost from solid core. One kind of such CT is the CT with flexible core (Figure 10.5c).

The constructions of transformers designed for current control in high-voltage transmission lines (160, 400 kV and more) differ considerably from the ones considered above due to special internal and external elements providing the required insulation level between the windings, and also between the windings and the case (Figure 10.6). The main insulation in such transformers consists of winding around of the primary turn by many layers of specific paper tape alternating with aluminum foil, and further filling of all free space with liquid transformer oil (Figure 10.7).

CTs and VTs are essential parts of relay protection systems in the power industry, where relays simply cannot be used without such transformers. Moreover, there are a number of peculiarities in the operation of such transformers, which require the relays to have specific characteristics. In this connection we have to consider in greater detail CT and VT.

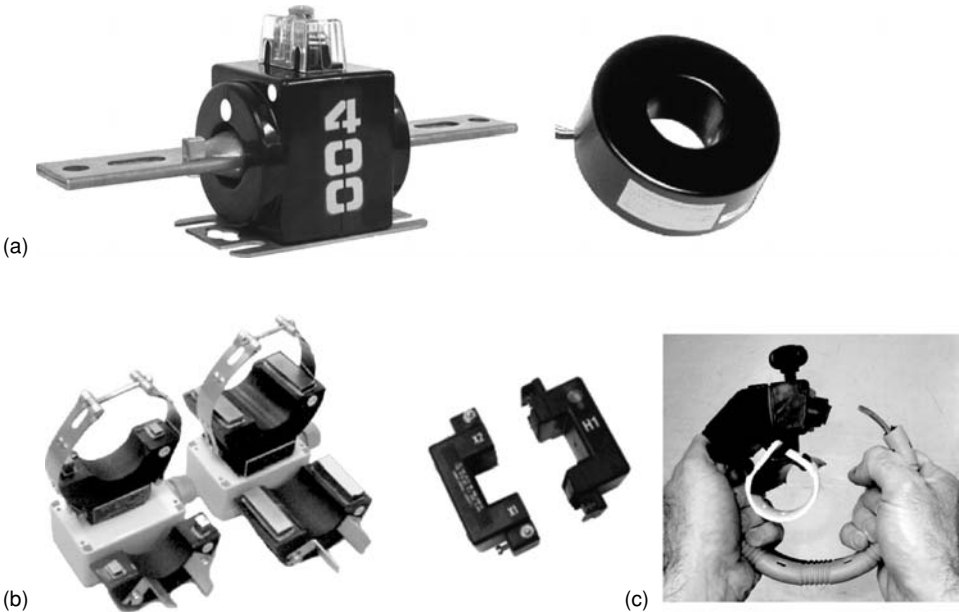


FIGURE 10.5
Modern CTs. (a) bushing and toroidal type; (b) split core; (c) with flexible core

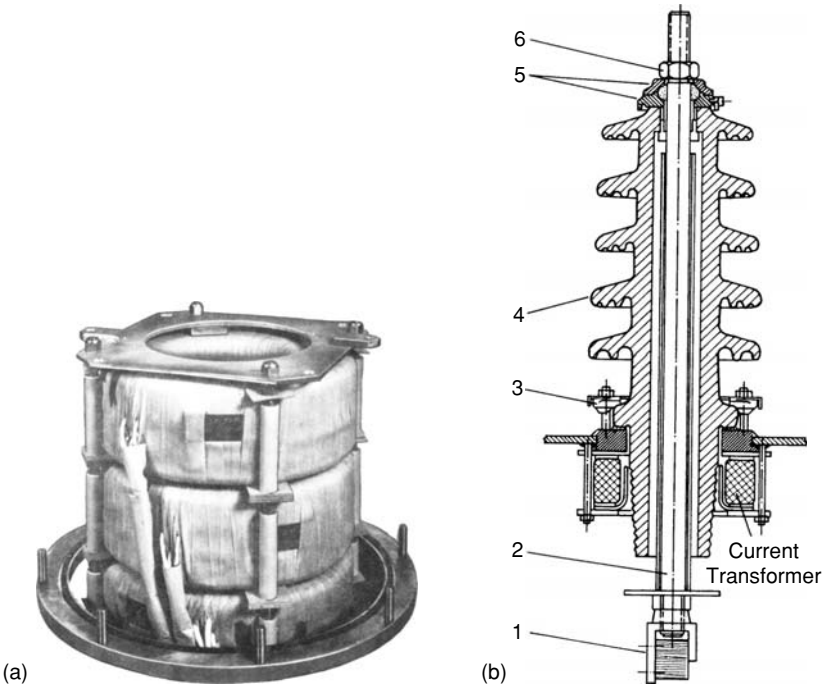


FIGURE 10.6
(a) Bushing CTs assemblies (three separate CTs). (b) Location of a single CT, or CT assemblies, on a power transformer's HV bushing. 1 — Lower connecting piece; 2 — undoing connection bolt; 3 — lower fastening; 4 — replacing porcelain; 5 — head armature; 6 — loosening nut.

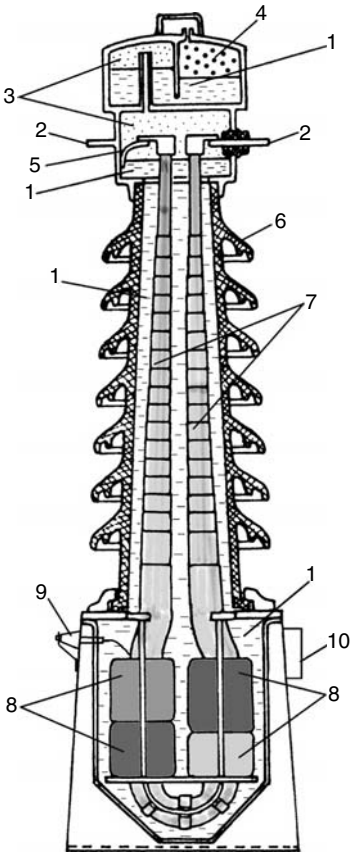


FIGURE 10.7

One of the most widespread constructions of a high-voltage CT (160 kV), with oil-impregnated paper insulation. 1 — Oil; 2 — copper plates for connecting to the controlled current circuit; 3 — volumes filled with nitrogen; 4 — air; 5 — jumper strap linking one of the outlets with the metal case of the upper reservoir; 6 — porcelain insulator; 7 — insulated primary conductor (primary turn); 8 — four independent secondary windings, each with its own magnetic core; 9 — insulator on the outer wall of the tank, with the outlet connected to the tank; 10 — terminal box with outlets of secondary windings.

First of all, the construction diagram in Figure 10.7 is not the only one that exists. Secondary windings with cores can be placed not only on the lower part of the transformer but also in the center, and even on the upper part (Figure 10.8). The traditional scheme, with a lower position of secondary windings, allows us to place the center of gravity of the construction very low, providing high resistance of the upper transformer to turnover. Upper position of the secondary windings, on the contrary, sharply reduces transformer resistance but allows us to simplify and reduce the price of construction of the high-voltage insulation. Availability of windings entirely separated from each other, supplied with separate magnetic cores (these are windings with different parameters and characteristics as a rule) means that in the case of a CT there are several (usually three to four) separate CTs, the primary windings of which are cut into the common controlled current circuit.

The “head” of the transformer, that is an upper metal reservoir, has a complex construction with many barriers, tubes, and valves. There is more than one purpose for this part of the transformer. First, it serves as a shield equalizing the electric field in the area of current outlets connected to the high-voltage line, which is why one of the outlets of the primary winding is connected with the internal (in some construction, external) bridge to the reservoir. Second, this reservoir serves as damper absorbing excess of oil from the main part of the transformer when the temperature increases. Third, this reservoir, with the help of the so-called water seal, prevents transformer oil contact with outdoor air containing moisture.

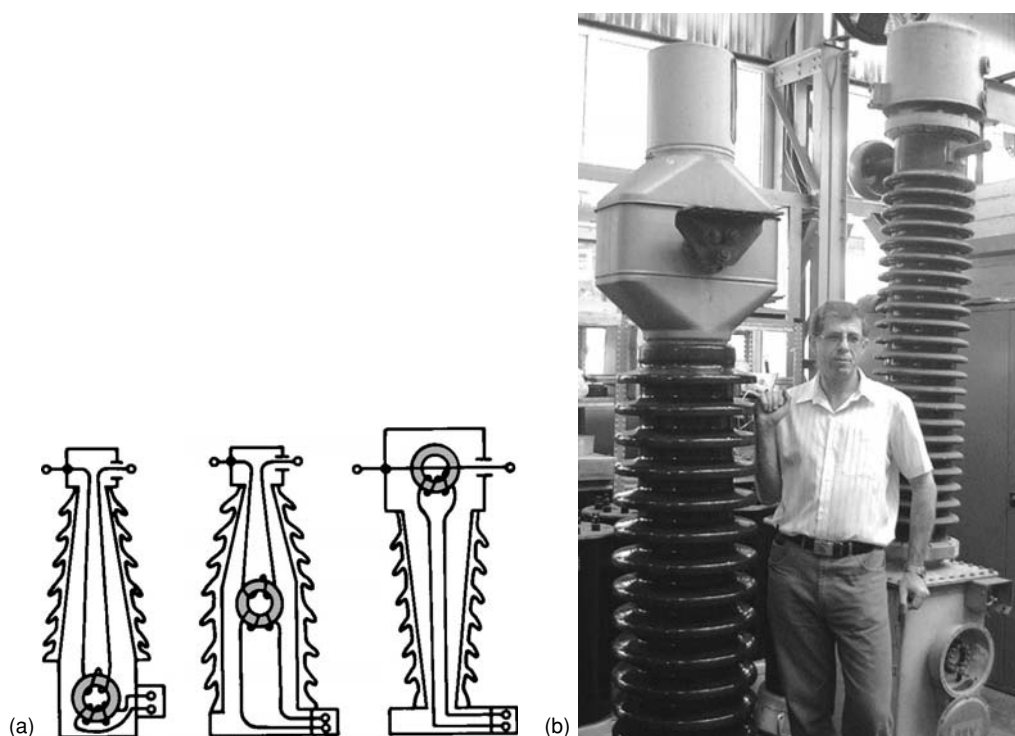
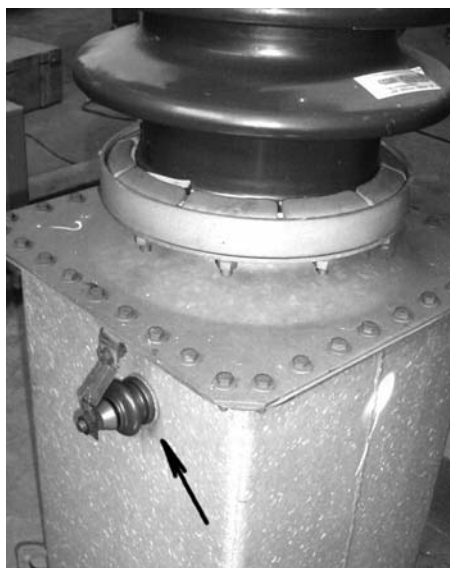


FIGURE 10.8

(a) Construction diagrams and (b) external design of high-voltage oil-filled CTs. In the photo: to the left — with upper; to the right — with lower position of windings.

The purpose of the aluminum foil layers (or a thin grid of aluminum foil, to be more exact) in the main insulation of the primary turn is even more interesting; at first sight it may seem that inclusion of metal layers to the insulator is unnatural.

You may be even more surprised to learn that the outer layer of this foil is linked with a special outlet placed on the outer surface of the transformer tank, and that this outlet is not a simple one. It passes through a small ceramic insulator (9) and is grounded with the help of a bridge to the tank ([Figure 10.9](#)). Why is this outlet insulated from the tank with the help of an additional insulator, and then connected by the bridge to the same tank? What a strange conglomeration of structural components absolutely absurd at first sight? In fact everything has its important purpose. Metal foil, for example, serves as an electrode of the capacitor, forcedly equalizing high-voltage distribution by the thickness of the insulating layer, and also as an electrostatic shield equalizing local electric field strengths in the transformer construction. This allows enhanced reliability and enhanced service life of the high-voltage insulation. The additional insulator on the tank, through which the conductor linking the foil with the grounded tank comes out, is used only for diagnostics of the high-voltage insulation state. As the foil inside the tank is fully insulated both from high potential and from ground potential, if one measures such insulation characteristics as resistance, capacity, polarization index, and the dielectric dissipation factor between the external outlet (9) of the foil, and the outlets connected to the high-voltage circuit, one can make conclusions about the state of some parts of the high-voltage insulation of the transformer (unfortunately, a more thorough consideration of these problems is beyond the limits of this book). The second part of the insulation is

**FIGURE 10.9**

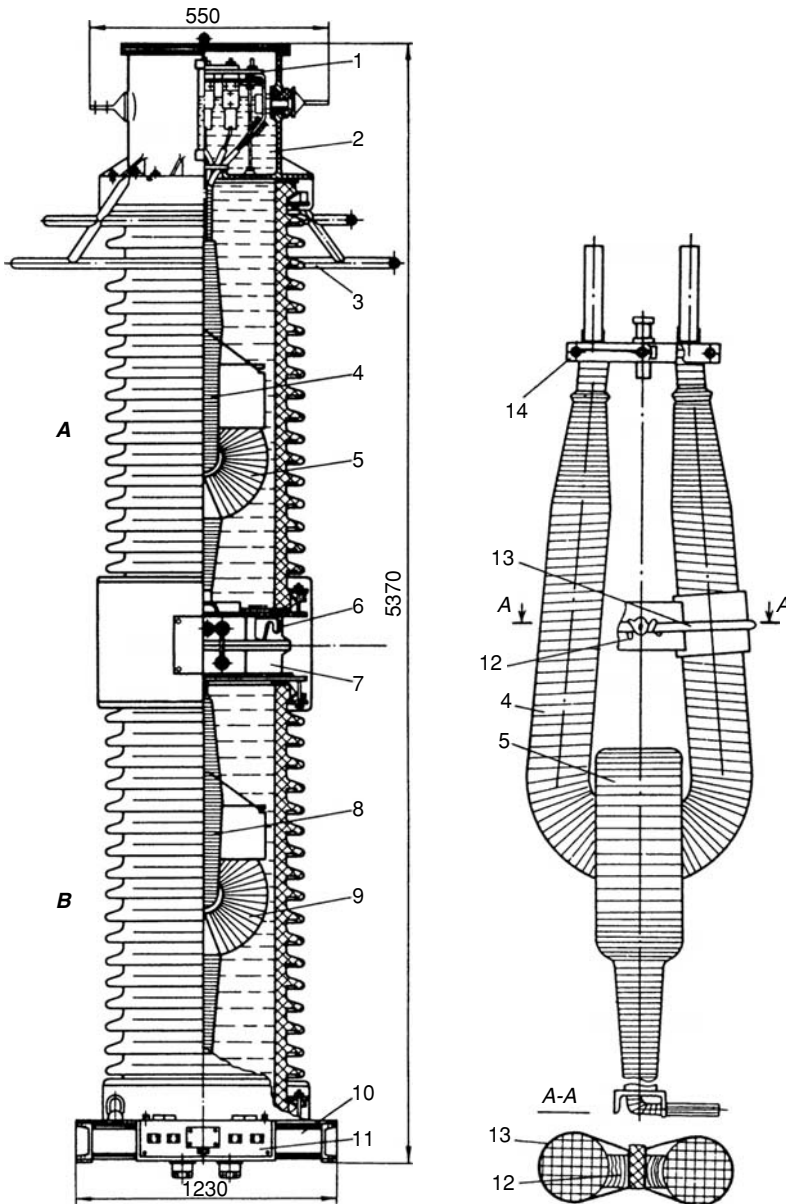
Test outlet of an oil-filled CT of the 160 kV class, designed for control of the high-voltage insulation state.

**FIGURE 10.10**

CT of the 420 kV class, with sulfur-hexafluoride (SF_6) insulation (A Reyrolle & Co. Ltd).

checked between the outlet (9) and the grounded tank of the transformer. As these measurements take place at relatively high voltages, the outlet (9) must be well insulated from the tank. With measurements completed, the outlet (9) is again connected to the tank with the help of the bridge.

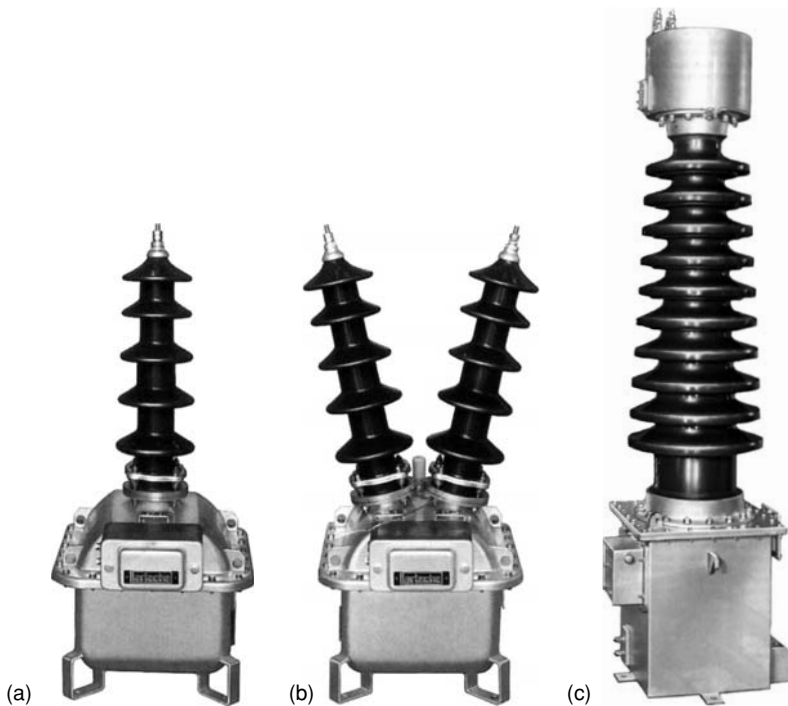
In sealed switchgears with gas insulation, filled with sulfur-hexafluoride (SF_6), CTs of appropriate construction, also filled with this gas, are used (Figure 10.10). Once the necessity arises to use external CTs and VTs for voltages of 400 kV and more, cascade constructions consisting of two to three units connected in series, are used. Each of these

**FIGURE 10.11**

Cascade two-stage CT of the 500 kV class, of the TF3M500 type (Russia). 1 — Switch of turns number of the primary winding; 2 — oil-conservator; 3 — high-voltage shield; 4 and 8 — primary windings of units 5 and 9 — secondary windings of units; 6 — eye; 7 — base; 10 — heel piece; 11 — terminal box with outlets; 12 — block; 13 — fixing band; 14 — holder.

units is a self-contained transformer (Figure 10.11). An interesting peculiarity of the CT construction, shown in Figure 10.11, is a switch (1) also linking sections of the primary winding (four single-turn U-shaped sections) in different combinations, in series or parallel, providing values of nominal primary currents: 500, 1000, and 2000 A.

In a CT the primary winding consists of the first half-turn, with very low resistance, while in a VT the primary winding has many turns and possesses very high impedance

**FIGURE 10.12**

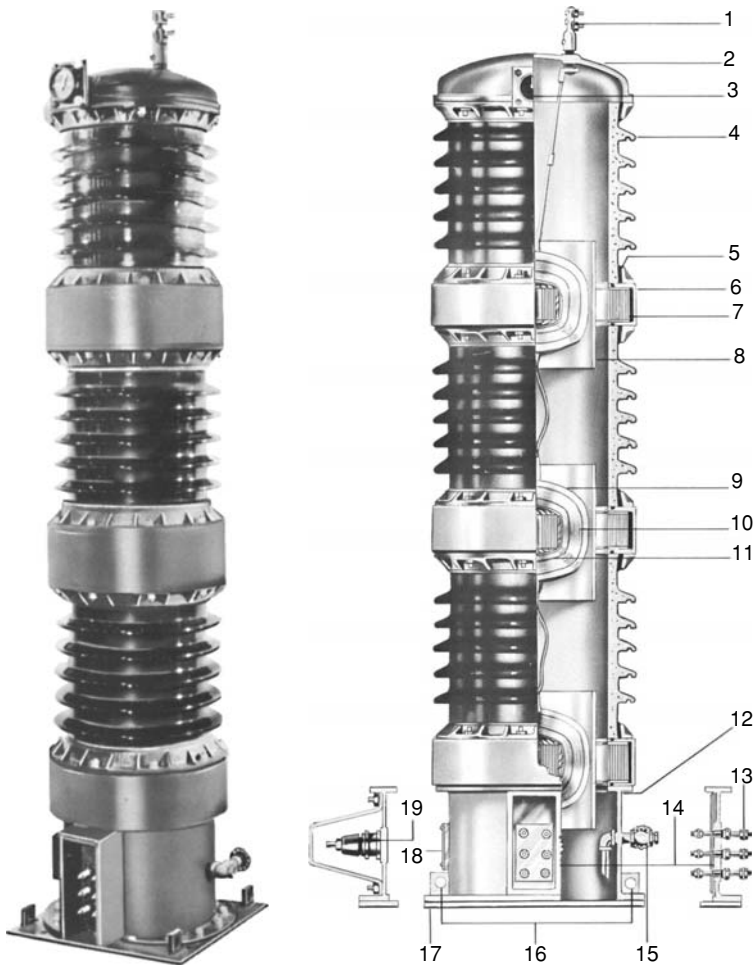
VTs of the 33 kV (a) and (b) and 145 kV (c) class.

because the total working voltage is applied to this winding. When the primary winding is switched to the so-called “phase” voltage, which is between the phase of high-voltage and the “ground” (the most often used connecting mode of a VT), only one outlet of the winding is supplied with a high-voltage outer insulator. Its second outlet is usually linked with the VT case (as a rule, with the help of an additional small insulator on the tank), which has similar construction and for some constructions (usually at voltages of no more than 36 kV) both transformer outlets may have high-voltage insulation (Figure 10.12b).

For very high voltages this so-called cascade construction is used. It consists of several transformers, connected in series and placed in the same case (Figure 10.13), and also of transformers of the capacitor type (Figure 10.14). The principle of operation of the latter differs greatly from all others. In fact one can hardly call them transformers. According to their principle of operation, these devices might belong to voltage dividers rather than to transformers (Figure 10.14b).

As can be seen in Figure 10.14a, a transformer for a voltage of 800 kV has quite an exotic design, due to two toroids, in the central part and at the upper point. These toroids are made of separate elements — as a rule aluminum ones, with a semicircular polished surface, and serve the purpose of equalizing the electric field and reducing its strength. Recently, capacitor-type transformers have also been produced for lower voltages (Figure 10.15).

Like in any voltage divider, in the capacitor-type VT (Figure 10.14b) there is a high-voltage arm (C_1)-on which the bulk of the high-voltage drop, and a low-voltage arm (C_2), from which the low level voltage appears. In fact, the high-voltage arm is formed not by one, but by several capacitors (a VT of 765 kV class contains 6 such capacitors), connected in series, which are easy to see in constructions of such transformers. In some VTs the

**FIGURE 10.13**

EU type oil immersed cascade VT (General Electric Co.). 1 — HV terminal; 2 — dome-shaped cover; 3 — liquid-level gage; 4 — porcelain shell; 5 — clamping ring; 6 — cylinder assembly; 7 — formed core; 8 — insulation barriers; 9 — coupling winding; 10 — primary winding; 11 — secondary and tertiary winding; 12 — base tank; 13 — secondary and tertiary terminals; 14 — terminal housing; 15 — drain valve; 16 — eye-bar for lifting a complete VT; 17 — bolter base plate; 18 — nameplate; 19 — neutral (ground) bushing. (General Electric Instruction GEH-1629H.)

low-voltage arm is supplied with a throttle (L) and a low-VT (T) providing the VT with characteristics similar to a standard coil VT. The capacitor-type transformers are much cheaper than the standard ones at high voltage levels, and are not prone to such VT “diseases” as “ferro-resonance,” which usually leads to the “lethal outcome” of the VT and severe accidents in the circuit.

CTs and VTs of the opto-electronic type have been developed for a few decades in many countries (Figure 10.16). They are based on the application of Kerr and Pockelce electro-optic effects (for voltage measurements) and the Faraday magneto-optic effect (for current measurement). The Faraday effect can be found in the rotation of the polarization plane of linearly polarized light in optically active material, caused by an external magnetic field.

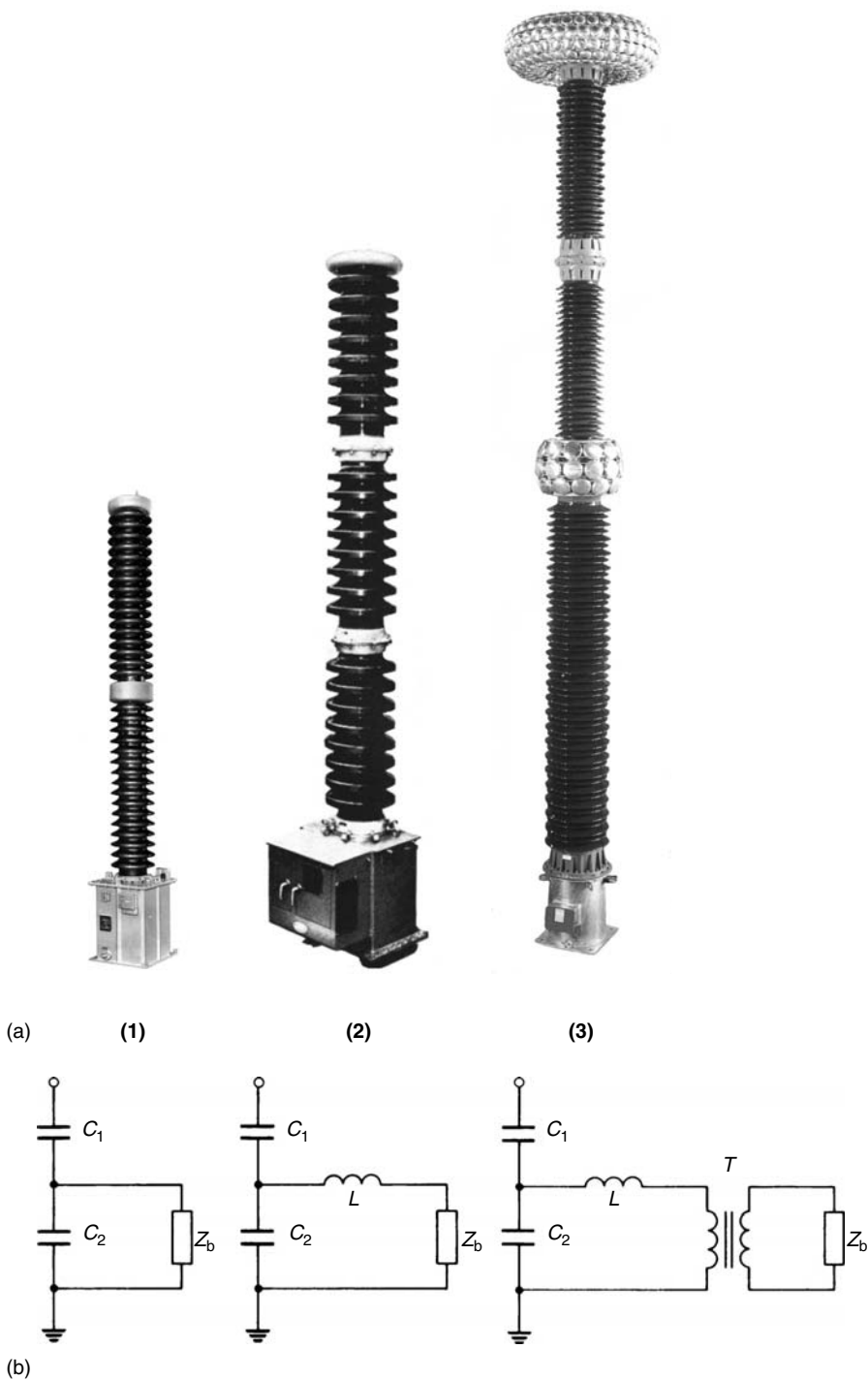


FIGURE 10.14
(a) High-voltage VTs of capacitor type of the 345, 362, and 800 kV class. (b) Principle of construction of VTs of the capacitor type.



FIGURE 10.15
A capacitor-type VT, for voltage of 24 kV (Passoni Villa, Italia).

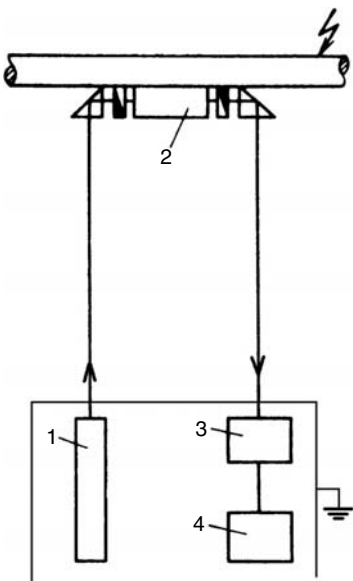
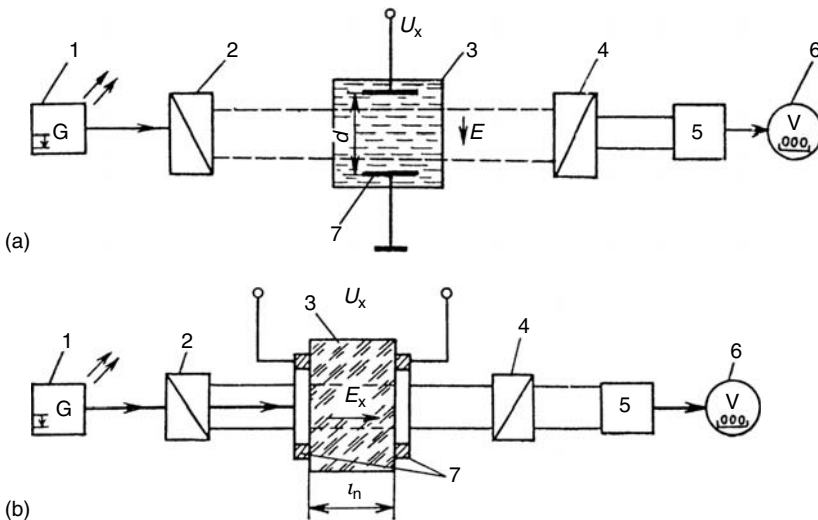


FIGURE 10.16
Principle of construction of an opto-electronic transformer. 1 — Source of polarized light; 2 — electro-optical transducer; 3 — light analyzer; 4 — photo-transducer and amplifier with an outlet final control element.

If the transducer is placed in the magnetic field of the measured current, one can determine the current strength by measuring the angle of rotation of the plane of light polarization. As a working substance in magneto-optical converters, glasses containing lead oxide (so-called flints, crowns) are usually used, and also fused quartz. Iron–garnet films are especially sensitive to magnetic fields. In this device (Figure 10.16) the polarized ray from the grounded source comes through an optical fiber (or through any other type of light-guiding fiber) to the Faraday cell (2), placed on the high potential. In this optical cell the light flux changes its polarization vector, depending on the value of the magnetic flux affecting it. At that point the light ray, modulated in such a way, returns to the ground potential, where it is converted to electric current and is amplified.

In VTs Kerr or Pockelce’s cells are used instead of Faraday cells (Figure 10.17). The light flux in them is modulated not by the magnetic field but by the electric field in the active material placed between the electrodes, to which the measured voltage is applied. The

**FIGURE 10.17**

Electro-optical transducers of Kerr (a) and Pockelce (b). 1 — Light source; 2 — light polarizer; 3 — active material; 4 — polarization analyzer; 5 — photo detector; 6 — output element; 7 — electrodes to which the measured voltage is applied.

Kerr effect occurs in many isotropic substances (benzene, epoxy resin, etc.), very often nitrobenzene, which produces the biggest effect, is used. The Pockelce linear electro-optic effect can be observed in piezoelectric crystals placed into the electric field. This effect is seen most apparently in crystals of ammonium dihydro-phosphate ($\text{NH}_4\text{H}_2\text{PO}_4$) and potassium hydro phosphate (KH_2PO_4), in the longitudinal electric field created by ring electrodes (7), (Figure 10.17b). Pockels cells typically work with five to ten times lower voltages than the equivalent Kerr cell.

Such devices have been designed for the last 30 to 40 years already, but only recently have optical transformers appeared on the scene. The NxtPhase Optical Current Sensor replaces conventional CTs and brings a new level of accuracy to current sensing over a range of 1 A (rms) to 63 kA (rms), from 115 to 500 kV (Figure 10.18). The sensor is based on the Honeywell Fiber Optic Gyro system, which has a trusted reputation for accuracy and reliability in aeronautic and space industries for both commercial and military applications. The sensor can be column mounted on an advanced polymeric insulating column, or bus mounted with a suspension insulator to bring the optical fiber to ground.

The NxtPhase Optical Current Sensor consists of a specialized opto-electronic convert signal (1) from a light emitting diode into two linearly polarized signals, both sent through a polarization maintaining optical fiber to the sensing head. At the top of the column there is a circular polarizer (2) that converts the two linear-polarized light signals into right and left circular polarizations. The light signals (3) travel around the conductor many times. The magnetic field created by the current flowing in the conductor slows one signal and accelerates the other (the Faraday effect). As the circularly polarized signals complete their path around the conductor, they are reflected by a mirror (4) and travel back through the fiber, the direction of their polarizations having been reversed. Along this reverse path, the effect is doubled. Both signals make their way back to the circular polarizer, which converts them back into linearly polarized light beams. Light 6 travels back down the column to the opto-electronics (1). The difference in the speed of propagation has been translated into a phase shift between the linear signals. Since both signals

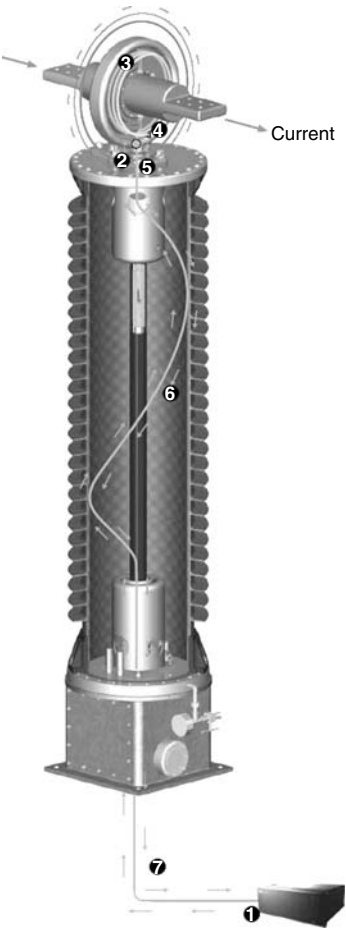


FIGURE 10.18
Optical CT developed by the NxtPhase Corp. (NxtPhase Co. catalog 2005).

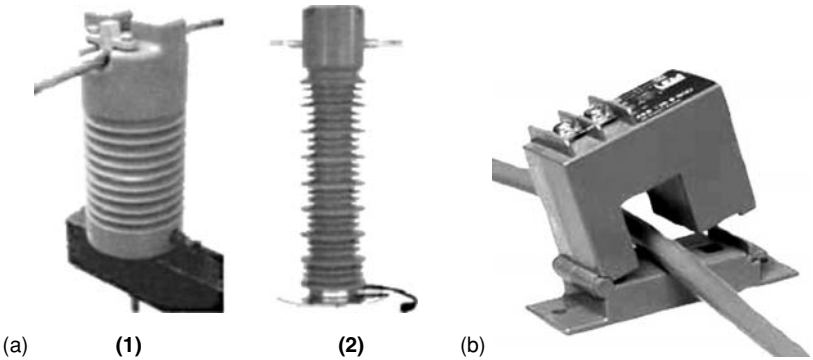


FIGURE 10.19
(a) Hybrid current-voltage sensors produced by Lindsey (U.S.A.). Insulating class: 15 to 35 kV (1) and 69 kV (2). Current ratio 600:5 A. (b) AKS series device — combine a current sensor and a relay in a single split-core package (LEM online catalog 2005).

have traveled an identical path, vibration and temperature changes have affected them equally — the highly accurate current measurement remains unaffected.

Hybrids of CTs and VTs are also produced in lots. In fact, CTs or VTs are never used alone in electric power stations or substations. They are always used together. Very often both the CTs and VTs are switched to the same high-voltage line. Each of them is equipped with expensive high-voltage insulation. It occurred to the engineers of the Lindsey Company (U.S.A.) to combine a current and a voltage sensor in one construction, so a hybrid of them appeared (Figure 10.19), which is much cheaper than two separate transformers and which uses less place than is necessary for two separate transformers. For the time being such hybrids do not have very high characteristics for current and voltage, but they are sufficient for many practical applications.

Other interesting hybrids are the combination of current sensor and protective relay in a single package (Figure 10.19b). LEM Components has introduced families of current monitoring relays that uniquely combine a current sensor and a relay in a single split-core package. By requiring fewer connections, the new devices offer increased reliability and up to a 50% reduction in installation time. This makes them particularly suitable for cabinet applications in process automation. The new product families are available for AC current (AKS series) and DC current (DKS series) from 1 to 200 A. They can be powered internally or externally. The output can be normally open or normally closed with a solid state or a dry contact relay compatible with AC or DC secondary circuits. The design's clamp-on function allows mounting on site without splitting conductors, reducing the number of actions (no disconnection of the cable) and cutting installation time still further thereby increasing safety.

The most important characteristic of VTs and CTs is their accuracy, which greatly depends on their load level, and for CTs also on the current ratio in the primary circuit. As we know, other conditions being equal, current I in the circuit depends inversely on the load resistance R : $I = U/R$. But this means that current in the input circuit of the current relay will depend on resistance of the input circuit itself, which is on the parameters of the relay. And what shall one do if several relays of different types are connected to the same CT? What accuracy can we speak about in this case? Actually, current in the secondary circuit of the CT (unlike in all other transformers types) does not depend on the resistance of the load. And does the Ohm's law work? It does. Only not the law for a sub-circuit:

$$I = \frac{U}{R}$$

but rather this one, for a whole circuit

$$I = \frac{U}{R + r}$$

where R is the resistance of the load, and r is the internal resistance of the source, that is impedance of the secondary winding of the CT. Under the stipulation that $r \gg R$, the current in the circuit does not depend on the resistance of the load (relay coil).

In standard power transformers which are so-called "voltage sources," the resistance of the load is much higher than the internal resistance of the windings ($R \gg r$), which is why the load current is inversely proportional to its resistance. The CT operates in the mode of "current source" and differs from all other transformers by the fact that the resistance of its secondary circuit is higher than the resistance of the load, and that determines the current in the circuit. The secondary current depends only on the primary

current and on the transformation ratio. In order for the CT to operate well in this mode, the load resistance cut in to the circuit of the secondary winding must be very small. The CT operates well even with fully shorted secondary winding, and vice versa; it “feels bad” if the load resistance gets high or the secondary circuit appears to be broken. In the latter case, the CT works as a step-up transformer with a large transformation ratio and the voltage level on terminals of the secondary winding may reach several thousands of volts (Figure 10.20). Such voltage is dangerous, and besides it may lead to damages of insulation of the low-voltage secondary winding. There have been cases of explosion of CTs caused by gases accumulated in the transformer because of long-term exposure to partial discharges at an open-circuit winding, which is why such mode of operation of the CT must be ruled out. In cases where, in multi-winding CTs, some windings are not used, they must be shorted by jumper straps. To protect the CT from spontaneous opening of secondary circuits the author suggested the use of simple electronic devices which short-circuit the secondary winding of the CT in cases of inadmissibly high voltage on it (see V. Gurevich, *Protection Devices and Systems for High-Voltage Applications*, 2003, Marcell Decker, NewYork).

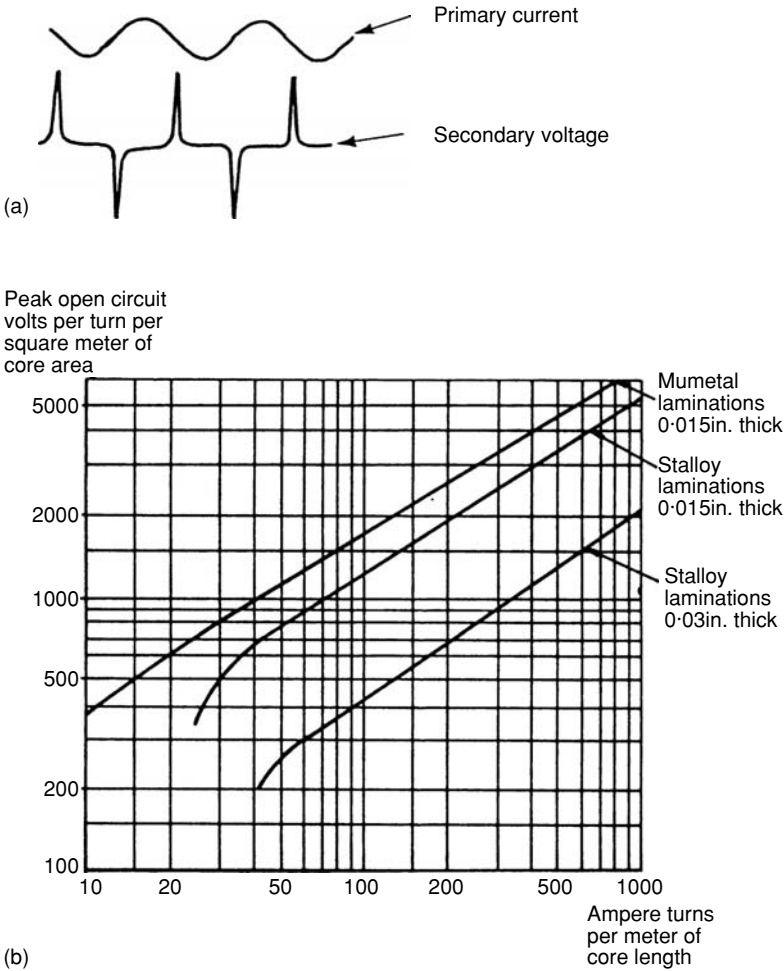
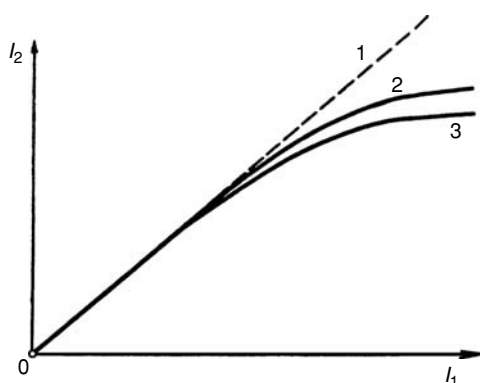


FIGURE 10.20
(a) The voltage shape and (b) level on the terminals of the secondary open-circuit winding of the CT and the voltage amplitude, depend on construction peculiarities and the current in the primary winding of the CT.

**FIGURE 10.21**

Dependence of the secondary current (I_2) on the primary one (I_1) in the CT. 1 — Ideal curve; 2 — actual curve with rate burden $Z_{2\text{ nom}}$; 3 — actual curve for large burden $Z_2 > Z_{2\text{ nom}}$.

As in any other technical device, losses also take place in CTs. Because of these losses not all primary current is transformed to the secondary circuit. Such losses may cause current error in the CT. In addition, current in the secondary circuit is slightly displaced in phase with regard to primary current, which causes angle error of the CT. Losses in CTs depend mostly on the state of their magnetic circuits. Until the magnetic core iron is saturated, there remains a directly proportional dependence between primary and secondary currents. When the primary current rises, the degree of saturation of the magnetic core iron increases as well, and the corresponding characteristic begins to turn down (Figure 10.21), and when the CT load increases, the degree of deviation of the characteristic increases as well (as the demagnetizing effect of the secondary current decreases).

To estimate the condition of the iron of the CT, its volt-ampere characteristic is read while gradually increasing alternating current is applied to the secondary winding, and the voltage on the terminals of this winding is measured. At that point it is compared with its manufacturing characteristic (Figure 10.22). One should bear in mind that these characteristics are obtained for simulated conditions of CT testing and do not reflect real correlations between currents and voltages in normal CT operation, but they do allow us to trace some faults in CT, which is why they are always read from the CT when new equipment is put into operation or at periodic tests.

CTs designed for measuring purposes work within the nominal currents on the straight-line portion of the characteristic, which is why they possess fine precision. Measuring CTs are produced for the following accuracy classes: 0.2, 0.5, 1, 3, 5 (with the class number corresponding to the error in percentage).

CTs used with protective relays work in emergency modes with currents considerably exceeding nominal ones, that is the curvilinear portion of the magnetization curve (Figure 10.23). That is why the indication of CT classes for relay protection also contains primary current ratio limits with respect to its nominal value when the indicated error is still to be taken into account. For example, the indication 5P30 means that the error for that given CT does not exceed 5% at primary currents exceeding the nominal value by 30 times.

Other conditions being equal, in order to provide the given error, the load power connected to the secondary circuit of the CT must not exceed the nominal power of the CT. With the nominal current, the load power will be determined by its resistance:

$$P = Z_2 \times I_2^2$$

where Z_2 , load resistance; I_2 , secondary current.

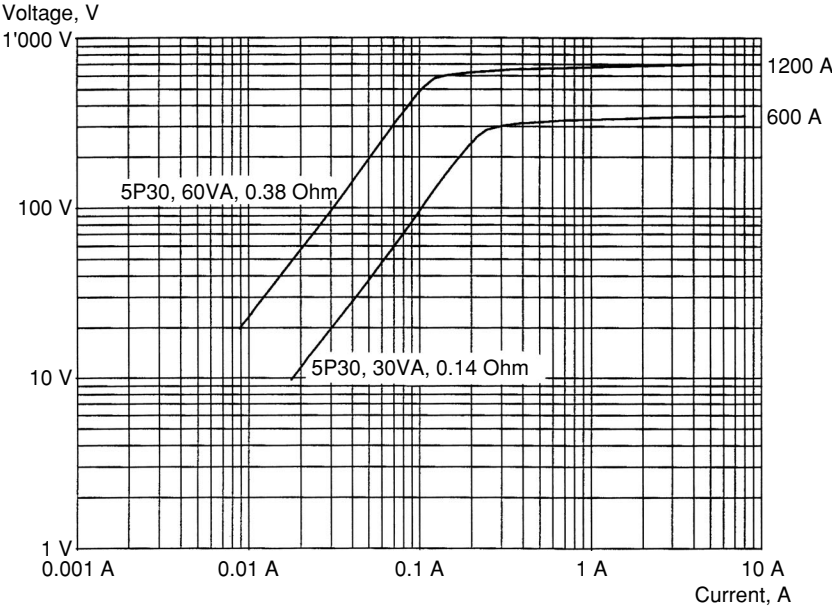


FIGURE 10.22 Actual volt-ampere characteristics of CTs with different transformation ratios are indicated in technical specifications.

That is why one can say that the lower the resistance of the external circuit connected to the CT, the less the loading degree of the CT and the less the error is. The character of the load affects the CT error considerably: an increase of the inductive load component leads to an increase of current error and a decrease of angle error.

There is a great variety of winding connections between the CT and the relay in three-phase networks. Some of them are shown in Figure 10.24. The scheme of the so-called “full star” (Figure 10.24a) responds to all types of short-circuits (between phases and one phase to ground) and is used in circuits with grounded neutral, in which short-circuit currents are possible even only in one phase. Simplified and cheaper circuits of the so-called “unfull star” (Figure 10.24b and c), are often used in electric circuits with an insulated neutral in which considerable short-circuit currents are possible only at a phase-to-phase fault, when considerable currents always flow in two phases. At any combination, fault of phases short-circuit current will flow through at least one CT. One can simplify the scheme even more by connecting the CT to the current difference between the two phases. In this case, it is enough to have just one current relay to protect a three-phase line.

On the scheme in Figure 10.24e, current in the circuit equals the vector sum of the secondary currents of the three phases. In the normal mode, this sum is about zero.

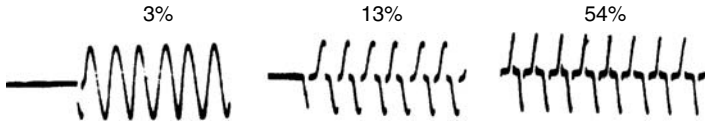


FIGURE 10.23 Forms of secondary currents in CT in emergency modes (overcurrents). The error of the CT is indicated in percentage points.

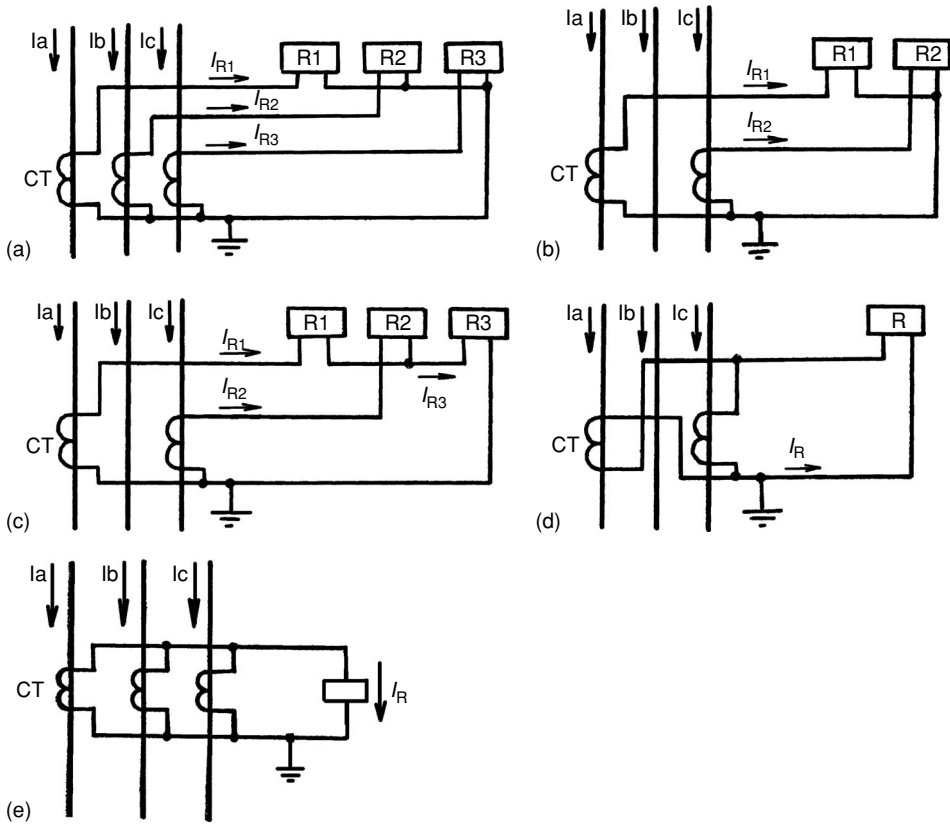


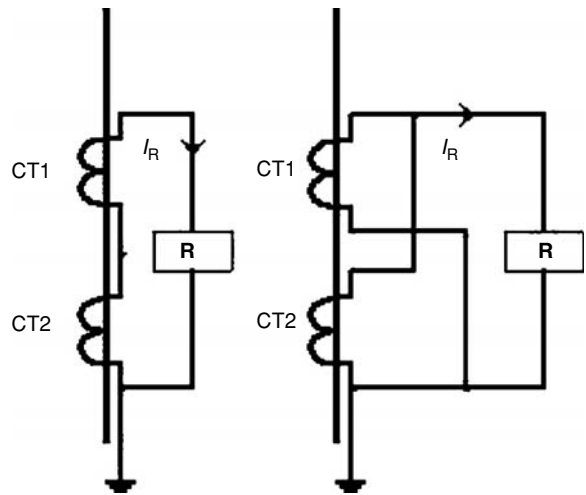
FIGURE 10.24

Some variants of connection of CTs and relays in three-phase circuits. CT — current transformers, R — current relays.

Current in the relay appears only when one or two phases are completed to the ground. Such a connection scheme is also called a “zero-sequence current filter.”

In some rare cases, two CTs (with the same transformation coefficient) are used rather than one CT, on the same circuit (in one phase). Their secondary windings are connected with each other in series or parallel (Figure 10.25). In series connections, the current in the load does not change in comparison with the current from one CT (that is, the transformation coefficient does not change either), and in parallel connections it equals the sum of both CTs (the transformation coefficient of the circuit is half as much as the transformation coefficient of one CT). In series connections of the CT, the load is proportionally divided between all CTs, which is why such a connection allows the use of low-power transformers to supply the load, consuming much power. Parallel connections are used for loads requiring increased current, or to obtain nonstandard transformation coefficients.

The error of VTs is determined by two components: by no-load current and by load current. Both cases involve additional energy losses. In the former case, these are losses caused by the magnetization of iron of the magnetic core. In the latter case, losses in the winding copper are caused by load current passing. The error from no-load current is usually much less than the error from load current; nevertheless obligatory checks of VTs imply no-load current measurements because it characterizes the state of the iron and the winding of the transformer. Like in the CT, there are two error components in the VC: by

**FIGURE 10.25**

Series and parallel connections of CTs in the same phase.

voltage and by angle (the phase displacement between primary and secondary voltage). The angle error much depends on the character of the load. If the load is active ($\cos \varphi = 1$), the angle error is negative. When the load is inductive ($\cos \varphi = 0.5$), the angle error turns to positive and increases linearly as the load increases. To lower, the VT voltage error for a nominal load, secondary voltage is artificially increased and one introduces a certain initial positive error maximum permissible during no-load operation. As the load increases, this initial positive correction is gradually compensated due to the negative error, and when it reaches the nominal load, the total resultant error turns out to be minimal. To unify and standardize the VT, it is usually designed for a secondary voltage of 100 or $100/\sqrt{3}$ V. As has already been mentioned, VTs are prone to so-called “ferro-resonance,” which can disable the transformer.

Ferro-resonance is a nonlinear resonance phenomenon that can affect power networks. The abnormal rates of harmonics and transient or steady-state overvoltage and overcurrents that it causes are often dangerous for electrical equipment. VT operation failures in distributing power circuits and in generator voltage circuits are quite common. On evidence derived from various sources, about 10% of installed VTs (for 6 to 36 kV) fail to operate annually in circuits with short circuit current to ground equal to 10 A. The parent cause of this phenomenon is the thermal destruction of the high-voltage winding of the VT by large currents, resulting in transformer core saturation and a drastic drop of its reactance (the main component of the impedance).

Usually the core saturation occurs during oscillation in the circuit, formed by circuit capacitance and transformer nonlinear inductivity. Such an oscillation process is initiated by unstable single-phase short-circuit to ground (Figure 10.26); partial phase operation of the VT itself results from the blow-out of fuses in high-voltage circuits; VT operation on “idle” buses; partial phase operation of the power transformer accompanied by overvoltages on the VT, etc.

The oscillations frequency may vary for different oscillation origins, parameters of the specific VT and specific circuits. In large VTs designed for 160 to 400 kV and more, the case in point is sub-harmonic frequencies 10, 12.5, 16.6, 25 Hz. In 6 to 10 kV distribution circuit VTs, the resonance frequency is due to attain 150 Hz.

It is worth mentioning that the processes occurring in the VT in these operation modes depends on a certain combination of the VT and the circuit parameters and their rating. Accounting for it is by no means easy (manufacturing variability of VT

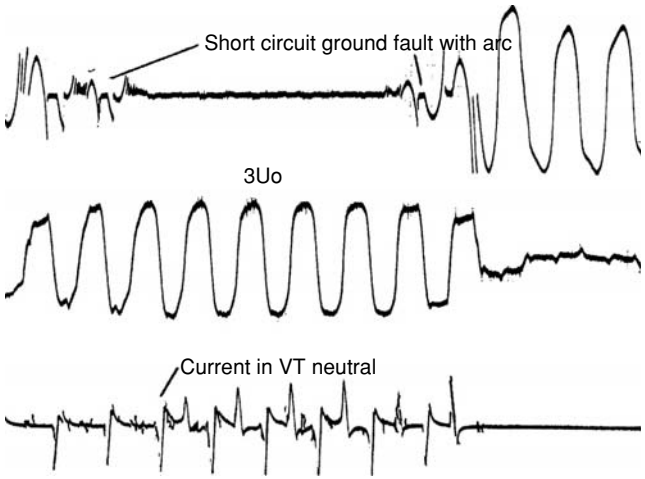


FIGURE 10.26
Oscillograms of current and voltage in a VT during a single line to ground short circuit.

parameters; circuit parameters variation; undefined parameters in transient regimes that caused the oscillation process, etc.). Therefore, different hardware is used to protect the VT from those regimes that impede or disrupt resonance once it occurs. For example, some manufacturers offer special ferro-resonance protecting devices for large VTs rated for 160 to 400 kV. The protecting device has an analyzer of the current spectrum in the VT circuit, which detects sub-harmonics emerging at low frequencies and subsequently generates an activation command in parallel with the secondary VT winding special throttle and active resistance of 0.3 to 0.7 Ω , which disrupts the oscillation process (Figure 10.27). Unfortunately, this device may have designer’s defects and may work very unreliably.

For medium-size VTs rated for 6 to 24 kV, simpler means are used. For example, for efficient protection against ferro-resonance of transformers with an “open triangle” type winding, it is a good practice to connect a 5 to 150 Ω resistance in parallel to this winding. Another common way of protection against ferro-resonance is to include a 3 to 5 k Ω resistor to the VT neutral terminal.

The author has not encountered reports that analyze the influence of such protection against ferro-resonance means on VT operation errors, but experience shows that designers ratings of VT loads (relay protection circuits, measurements, and registration of energy consumption) take into account only the nominal power range of the VT for

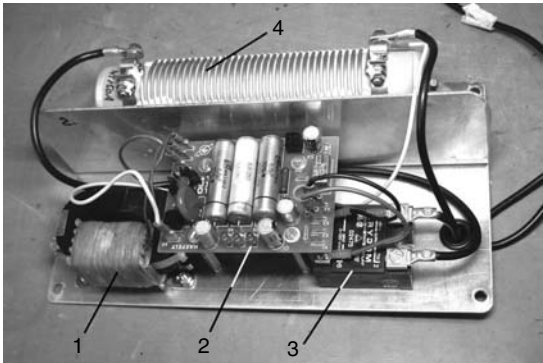


FIGURE 10.27
Device for VT protection against ferro-resonance (Haefelly). 1 — Chock of low frequency filter (16 Hz); 2 — electronic control board; 3 — solid-state contactor; 4 — low resistance noninductance resistor (0.5 Ω).

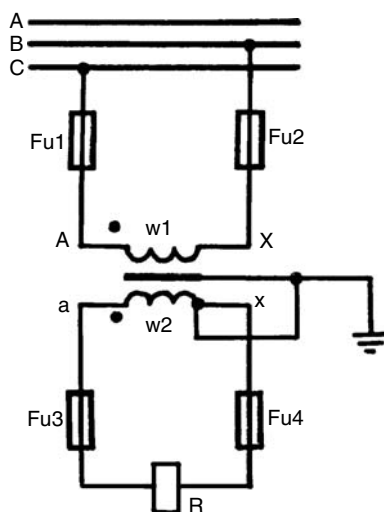


FIGURE 10.28

Connection scheme of a single VT of the 3 to 36 kV class for inter-phase voltage.

which its nominal accuracy level is preserved. However, some Western manufacturers supply VTs with antiferro-resonance resistors, which load the VTs to 60 to 80% of their nominal power. The result is overloaded voltage circuits; consequently VT operation error goes beyond the accuracy grade, and power consumption registration circuits powered by the VT result in heavy losses. There is no doubt that resolution of this problem will be provided by simple automatic devices, which connect resistors to the VT circuits only in response to ferro-resonance.

Some simple automatic devices for VT protection from ferro-resonance are suggested by the author in his books: *High-Voltage Automatic Devices with Reed Switch* (2001, Haifa) and *Protection Devices and Systems for High-Voltage Applications* (2003, Marcell Decker, New York).

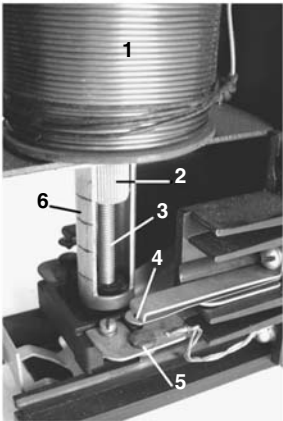
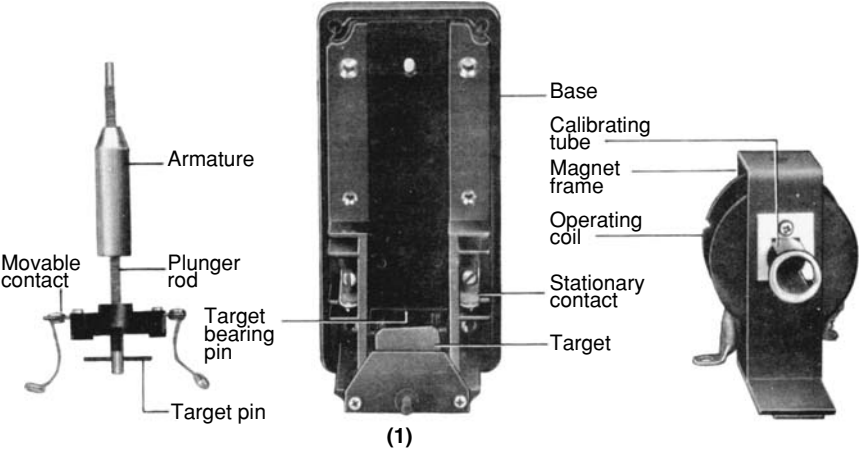
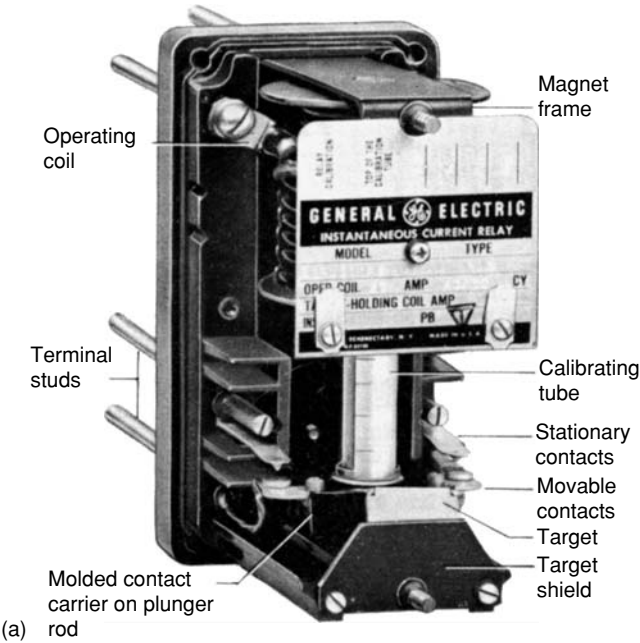
VTs for voltage up to 36 kV can be connected to interphase voltage, or between the phase and the ground. As a rule they are protected by fuses (Figure 10.28). High-voltage fuses (Fu1 and Fu2) cannot protect the VT when the circuit of low-voltage load is overloaded because of high internal resistance of the transformer. That is why additional fuses are installed in the low-voltage area. VTs of a higher class are connected phase-to-ground and do not contain fuses.

10.3 Instantaneous Current and Voltage Relays

The simplest and most widely used type of relay protection is the so-called “overcurrent cut-off” or “instantaneous current relay.” As one can conclude from the name, a relay designed for such protection must pick-up immediately without a time delay (TD) when current overpasses the predetermined (by adjusting the relay) value.

10.3.1 Protective Relays of the Electromagnetic Type

Electromagnetic relays of such type energized when the predetermined current threshold is overpassed (so-called “current relays,” which differ from standard electromagnetic



(b)

(2)

(Continues)



FIGURE 10.29 (Continued)

(a) Instantaneous current relay, PJC type (GE), with a retractable armature of the solenoid type. (b) Construction of elements and parts of the instantaneous current relay, PJC type. 1 — Operating current coil; 2 — knob-nut for adjustment position of armature in coil; 3 — plunger rod; 4 — fixed contact; 5 — movable contact; 6 — calibration scale. (c) Relay of PJC type with three independent units and three additional auxiliary relays with indicating flags. (General Electric Instruction GEH-1790A).

relays only by the winding containing a small number of turns wound around with thick wire, and by the unit of the adjusting pickup threshold).

Like in standard electromagnetic relays, in such current relays different types of magnetic systems described above are used. One of the simplest is a magnetic system of the solenoid type with a retractable armature (Figure 10.29). When current reaches a certain value, the armature is retracted to the coil and closes the contacts. When the current decreases, force of gravity makes the armature return to its initial position. The pick-up current is adjusted by revolving an adjusting nut (2) (Figure 10.29b). The initial position of the armature in the coil changes, and so does the threshold of the relay pick-up. The scale (6) is used for rough estimation of pick-up current. Relays of this type have been produced by the General Electric Company for tens of years, since the middle of the last century, and work successfully in thousands of electric power stations and substations around the world. The same principle is used to produce modifications of relays, with two and three independent relays mounted in the same case (Figure 10.29c), current relays with integrated auxiliary multi-contact relays.

Relays with three units, each of which is adjusted to a certain pick-up current, are used for selective three-stage protection of electric power lines. Every current protection device has a certain service area (work zone) on the protected line. This is caused by the fact that the wire of the power line has a certain impedance which considerably limits short-circuit current, if the point of fault is tens of kilometers of distance from the place of the current relay installation. In cases of such remote short circuits, the protective relay may not detect the fault (Figure 10.30). In the given example, when the short circuit occurs at the beginning of the line (point 1), current of about 1600 A flows through the relay (we mean both the relay and the CT). When the short circuit occurs at point 2, the current passing through the relay decreases to 900 A, and at the remote short circuit at the point 3, this current (less than 600 A) approximates the pick-up threshold of the relay (500 A). This relay will not respond at all to short circuits at points 4 and 5 because these faults are out of relay working zone. But how do we provide protection for a power line outside the working zone? The solution is, together with a relay providing instantaneous (INS)

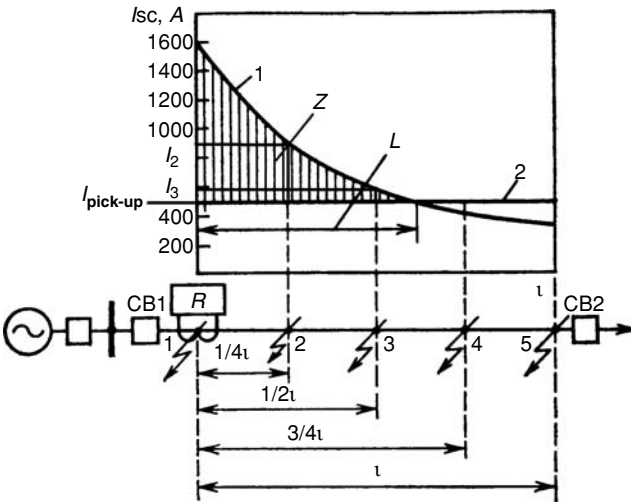


FIGURE 10.30 Diagram explaining the principle of operation of the overcurrent instantaneous (cut-off) relay on a portion of a long power line. I_{SC} — Short-circuit current at the point of the installation of the relay R ; I_{PICKUP} — pick-up current of the relay; L — maximum area of the protected zone Z ; CB — circuit breaker; I_2 — current passing through the relay when short circuit occurs at point 2; I_3 — current passing through the relay when short circuit occurs at point 3; 1 — curve of short-circuit variation along the line; 2 — zone of insensitivity of the relay.

current cut-off, an additional current relay with a TD is installed at the same place (Figure 10.31).

When short circuit occurs both protections installed in the substation (1) start to work in the cut-off, both the instantaneous cut-off and the TD. Obviously, the instantaneous cut-off will pick up first and disable the whole line with the help of switch $CB1$.

The TD relay will not pick up because of its TD, but if short-circuit current is not enough for the instantaneous cut-off pick-up (that is if the short circuit is out of its working zone), it is only the TD relay that will pick up because it is adjusted to a smaller current trip than the instantaneous relay current cut-off (that is, it has a larger zone of operation). First, it is necessary for protection of that part of line ($L1$), which remains out of the zone of operation of the cut-off relay INS (the TD Zone), and secondly it is needed for backup protection of the remote part of the line when the relay or the high-voltage circuit breaker malfunctions on other portions of the line. For example, if switch $CB2$ is not switched off for some reason, when a short circuit occurs on the part of the line $L2$, the

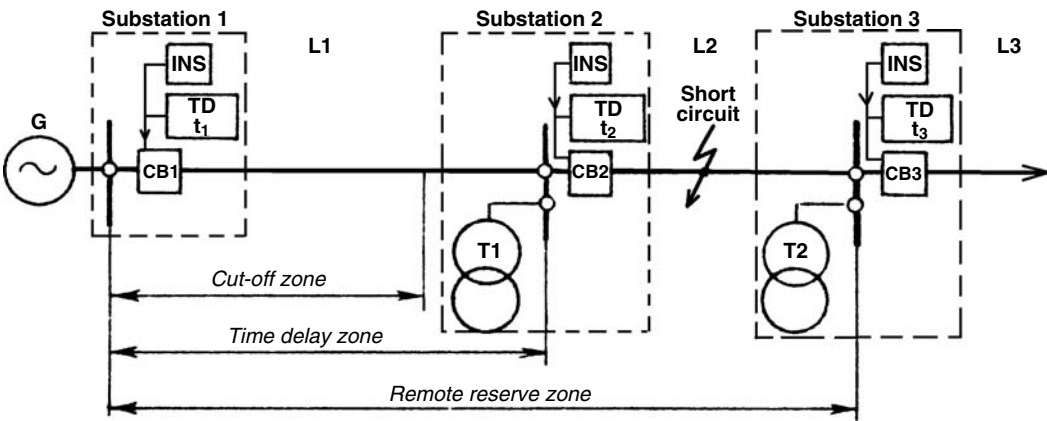
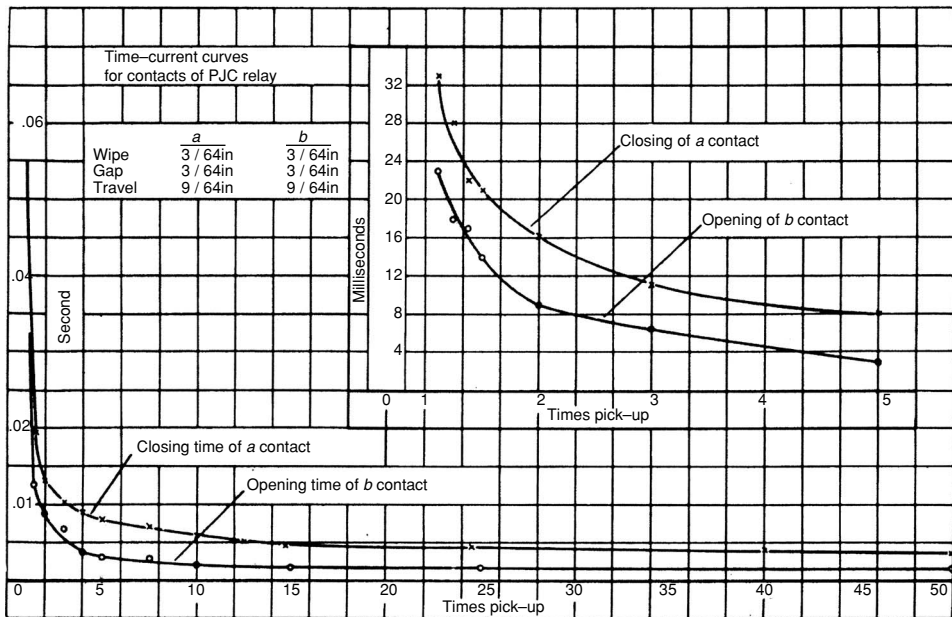


FIGURE 10.31 A composite single-line diagram of overcurrent protection for high-voltage transmission line. G — power source (power station); CB — circuit breakers; INS — instantaneous (cut-off) current relays; TD — time delay current relays; T — power transformers; L — parts of transmission line.

**FIGURE 10.32**

Time-current characteristic of the instantaneous current relay PJC. (General Electric Instruction GEH-1790A.)

second stage of the TD of the TD relay, installed in the first substation, will pick up and will disable the whole line with help of switch CB1. However, to prevent switching off of CB1 before CB2, and CB2 before CB3 in the normal mode, selectivity of operation protection must be provided.

The general principle here is as follows: the farther the protection from the power supply is, the smaller pick-up current it must be designed for, and the more TD it must have ($t_1 < t_2 < t_3$, Figure 10.31). The condition of selectivity of operation protection that must be provided is that the portion of the line closest to the fault from the power supply, is the portion that must be disabled. If the short-circuit current still does not disappear, the second portion, which is more distanced from the place of fault and closer to the supply, etc. Such an approach allows us to provide maximum survivability of the line, and maximum resistance of the line to faults.

Despite the term “instantaneous current” relay, it does have its own nonzero pick-up time, like any other relay. Moreover, the pick-up time of this relay depends on the current value in the winding. This should not surprise you if you recall the fact that the pick-up time of any electromagnetic relay decreases when the ratio of the voltage applied to the winding (or of the flowing current) with regard to its pick-up voltage (current) increases. Taking into account that a current relay works with high ratios of current in the winding, one can easily guess what kind of time-current characteristic it will have (Figure 10.32). It is worth mentioning that the construction of a relay with an armature of the plunger type can be used not only as a current relay, but also as a voltage relay — with winding, of course, which is wound around with a great number of turns of thin section. GE produced the so-called Ground Detector PJC type for the detection of grounds on ungrounded AC generator field circuits.

This relay consists of two plunger-type units (such as shown in Figure 10.29), a transformer, and a diode bridge, all in one case. The relay is operated from a grounded voltage source connected through one plunger-unit coil to the machine field circuit

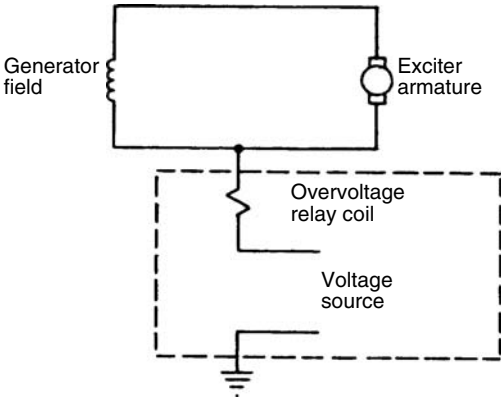


FIGURE 10.33
Typical external connections PJC relay, for detection of grounds on ungrounded AC generator field circuits. (General Electric Instruction GEH-1790A.)

(Figure 10.33). When a ground on the normally ungrounded field completes the circuit, the unit picks up.

The AC supply voltage is transformed, rectified, and filtered, producing a DC operating voltage for the relay with a ripple of one-half volt or less. This is applied between the ungrounded field and the ground. An indicating light on the front of the relay shows that the DC operating voltage is available.

One of the plunger-type units picks up if a ground develops on the field circuit. The other removes the operating unit from the grounded field and closes a contact for tripping or alarm. Reset is either by hand or electrically, through the test-reset switch. An AC machine field circuit is usually operated ungrounded, and a single ground does not damage the machine; however, a second ground can cause considerable damage, so protective equipment is therefore recommended to detect the first ground. The PJC type relay (Figure 10.33) serves this function. It can be used either to sound an alarm or to remove the load from the machine. The PJC type relay may be used with machine fields rated 375 V or less. It should not be applied where the exciter reverse voltage can rise above 500 V.

Voltage relays with a so-called “floating core” (a light core vertically “floating” in the magnetic field of quite a large coil) were investigated by Igor Gurevich (Kharkov, former U.S.S.R.) in the 1970s (Figure 10.34). He designed and constructed a lot of voltage relays



FIGURE 10.34
Igor Gurevich (1919–2003), designer of voltage relays with a floating core.

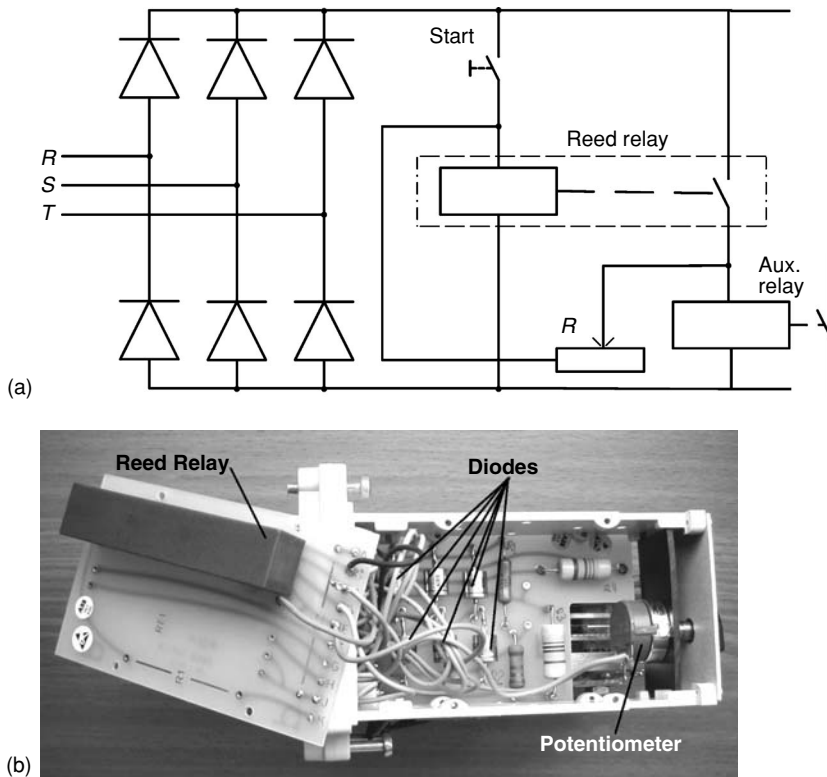


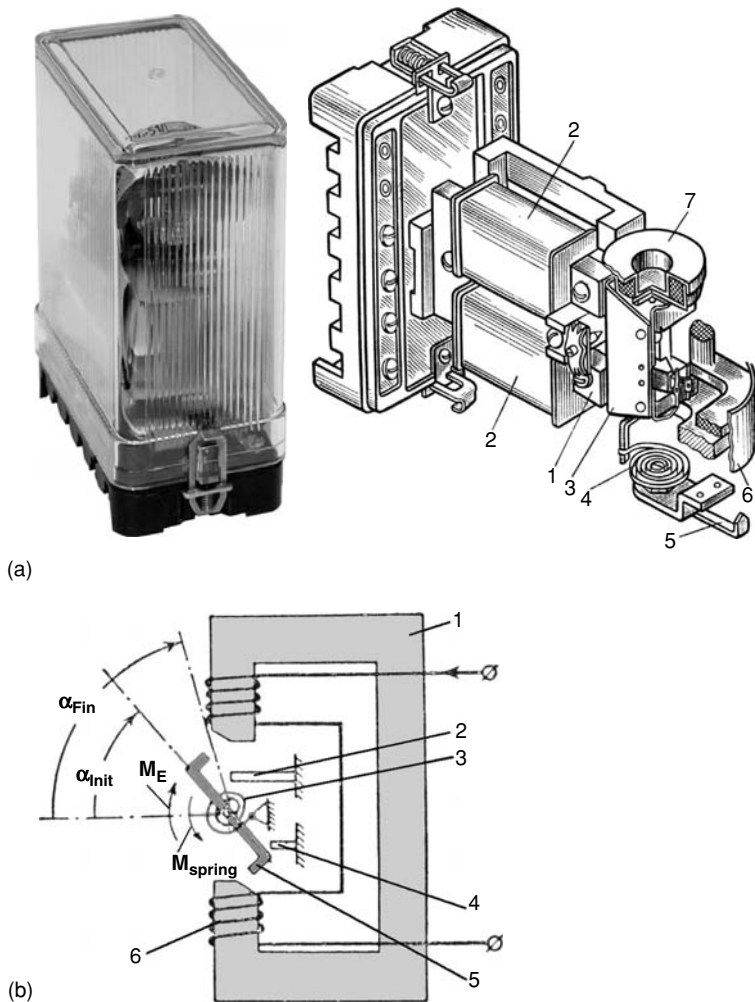
FIGURE 10.35
Simplified circuit diagram (a) and internal design (b) of the RXOTB-23 undervoltage relay.

based on the similar principle, with different types of the contact systems: from a standard microswitch to a mercury contact, a reed switch, and an optical photosensor. Such relays were used in different automatic control systems; automatic control with voltage level control, in which one such device was used both as a relay of overvoltage and a relay of undervoltage.

The RXOTB-23-type relay (ABB) has a very original principle and a simple design. This is a three-phase under-voltage relay that operates for symmetrical or asymmetrical voltage drops, or for phase failures (interruption in the AC supply). The RXOTB-23 is used, among other uses, as protection for control equipments and thyristor converters.

Three-phase input voltage is rectified in a six-pulse bridge having avalanche diodes, and is then supplied to a measuring dry-reed relay via a voltage divider having a variable resistor. The operating value is set with the aid of the resistor to between 50 and 100% of the rated voltage, and when any of the incoming voltages drop below the set value, the dry-reed relay disengages and interrupts the supply to the output auxiliary relay (Figure 10.35). After activation of the reed relay by the “start” push-button (and release “start” push-button, of course) its coil appears under the lowered voltage because of a voltage drop on the potentiometer. In this condition the slightest voltage reduction will be enough for the release of the reed relay. The level of release voltage is adjusted by the potentiometer.

Relays with a turning armature (Figure 10.36) were also widely used as instantaneous current and voltage relays. A Z-shaped turning armature was used in the ET-520-type relay, a predecessor of the RT-40 relay.

**FIGURE 10.36**

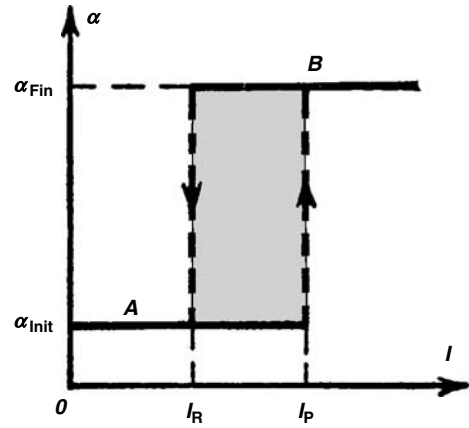
(a) A PT-40 type instantaneous current relay with a turning armature ($158 \times 130 \times 86$ mm), produced in the former U.S.S.R., and then in Russia, for the past 50 years. The first modification of this relay was called ET-520. 1 – Poles of the Π -shaped magnetic core; 2 – current coil; 3 – turning T-shaped armature; 4 – spiral spring; 5 – lever adjusting the spring tension (adjustment of pick-up current); 6 – scale; 7 – brake drum with sand. (b) Construction of the magnetic system of the ET-520 type current relay (Russia). 1 – Magnetic core; 2 and 4 – stops; 3 – spiral spring; 5 – Z-shaped turning armature; 6 – current coils. α_{init} and α_{fin} – initial and final angle of armature turning, respectively; M_E and M_{spring} – electromagnetic moment of rotation and counteractive spring moment, respectively.

This old relay had lower pick-up power than the PT-40-type relay (and therefore created a smaller load for the CT). The turning armature of both relays is constructed in a particular way, which provides increased reset ratio.

Use of a magnetic system of this type in measuring current and voltage relays is not a Russian invention. A current relay with a magnetic system similar to the famous one produced by Siemens was already described by Manfred Schleier in his book: *Die moderne Selektivschutztechnik und die Methoden zur Fehlerortung in Hochspannungsanlagen*, Berlin, Verlag von Julius Springer, 1936. That magnetic system was most likely invented long before 1936 if one takes into account the fact that the first protective relays were developed by the industry already at the beginning of the 20th century.

FIGURE 10.37

Typical characteristic of relay devices. A and B — extreme steady positions of the relay; α_{Init} and α_{Fin} — initial and final armature angle; I_P and I_R — pick-up and release parameter (current).



When we considered magnetic systems of standard (not measuring) electromagnetic relays, we mentioned that to increase the pick-up reliability (accurateness) of such a relay, an input value (of current or voltage) exceeding by 1.2 to 1.8 times the pick-up value of the relay must be applied to its winding. This excess is called the pick-up safety factor. Measuring relays adjusted for a certain level of input value must provide accurate and reliable pick-up at a gradual increase of the input value, and when it reaches the established level without any safety factor. Theoretically any relay by definition can take up only extremely steady positions, A and B (Figure 10.37). Here is how it happens: current in the relay winding creates a magnetic field in the core and in the working gap between the armature and the core. The magnetic field in the gap creates electromagnetic torque, affecting the movable armature in the direction in which the moving armature will reduce the air gap.

When the current in the winding reaches a value equalling pick-up current, the electromagnetic torque M_E of the relay will reach the nominal value $M_{E\text{nom}}$ (Figure 10.38), and the armature will begin to move. As can be seen in Figure 10.38, in the process of moving of the armature the electromagnetic torque $M_{E\text{Trip}}$ spontaneously

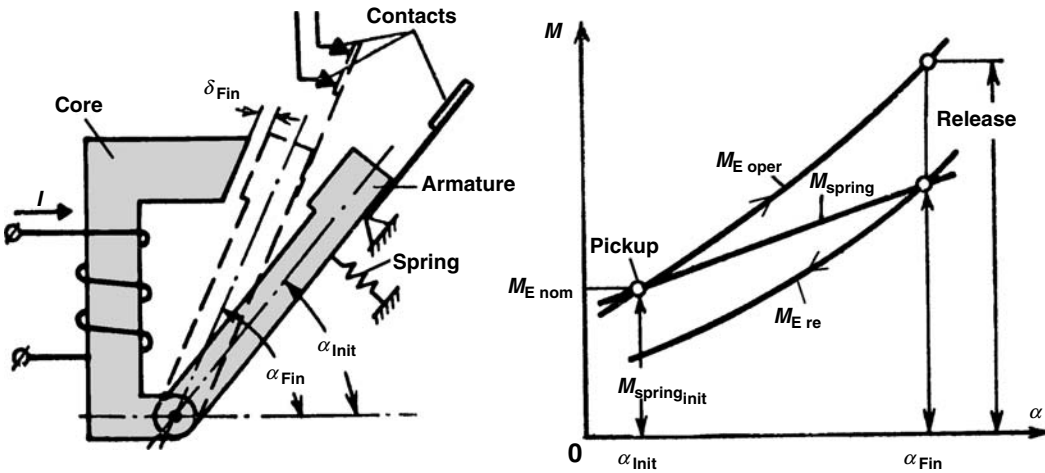


FIGURE 10.38

Pick-up process of an electromagnetic relay of the clapper type.

increases, while the current value in the coil remains the same. This happens because changing of the armature position (an increase of angle α) leads to a reduction of the air gap δ in the magnetic system (that is, reduction of the magnetic resistance of the circuit and an increase of the magnetic flux), so we have a circuit with positive feedback. As is well known such systems, when out of balance because of slight changes of the input value, cannot stop until they reach the new steady state (electronic circuits of this kind are called triggers).

Changing of the electromagnetic torque of the relay in the process of changing of the armature angle (or of the air gap in the magnetic system) is called the tractive effort characteristic of the relay. Changing of the counter torque of the spring in the process of changing of the armature angle (or of the air gap in the magnetic system) is called the mechanical (or load, or force, or displacement) characteristic of the relay.

It is clear that the relay will be in an ON state until its tractive curve will be higher than the load one. The intersection of these characteristics at a common point, means balance is achieved at that point, that is hovering of the relay in the intermediate position.

As can be seen in Figure 10.38, such balance is possible only at the initial point, when current has not yet started flowing in the winding and there is still no armature movement. As soon as $M_{E \text{ oper}}$ is greater than $M_{\text{spring init}}$, the armature pickups and begins to move and these characteristics do not intersect anywhere. When current in the relay winding is reduced to the initial pick-up current value, that is when $M_{E \text{ oper}}$ is reduced to $M_{E \text{ re}}$, the tractive effort curve of the relay (now $M_{E \text{ re}}$) is lower than the load curve M_{spring} , and the armature returns to its initial position.

The air gap in the magnetic system increases, the magnetic flux is automatically reduced (at constant value of current in the winding) and the relay quickly returns to its initial state.

It is obvious that the quality of the pick-up process of the relay and the release ratio (the width of the loop in Figure 10.39) is determined by the coordination of these characteristics. Throughout the long history of the development of relays there have been many attempts to create constructions with numerous springs and additional ferromagnetic elements, in an attempt to combine relay characteristics in the best possible way.

However, all of these previous attempts turned out to be too complicated and unreliable. Only traditional clapper-type relays, and relays of the solenoid type remain in practical use, although these too are still by no means the best solution, if one takes into account coordination of characteristics. In this sense more complex relays with a Z-shaped turning armature, possessing specific relay characteristics, appeared to be of a

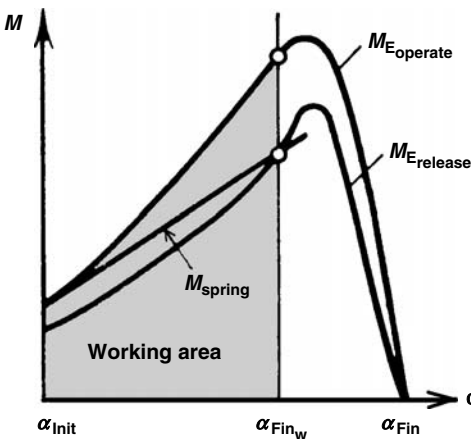


FIGURE 10.39 Characteristics of a relay with a magnetic system with a Z-shaped turning armature.

much higher quality (Figure 10.39). In relays of the clapper and solenoid types the air gap in the final position of the armature is minimal and the electromagnetic torque is maximal when the relay has picked up. This means that for return (switching OFF) of the relay, a considerable reduction of current in the coil is required. In contrast, in relays with a Z-shaped turning armature, there is no such sharp intensification of the electromagnetic moment when the air gap is reduced, because when the armature turns, the electromagnetic torque arm is reduced simultaneously. In the extreme armature position ($\alpha_{Fin} = 90^\circ$, Figure 10.36b) when the electromagnetic force developed by the coil is maximal, the electromagnetic torque decreases to zero (since the entire electromagnetic force is applied along the armature and the arm of force equals zero) and there is no value that can make it turn. Of course, the working area of the relay does not include this extreme armature position ($\alpha_{Fin} = 90^\circ$, Figure 10.36b). It is limited by the position $\alpha_{FinW} < 90^\circ$ because when $\alpha_{Fin} = 90^\circ$ the armature cannot create contact pressure. Nevertheless, the electromagnetic moment in the switched-ON position of this relay appears to be less than in relays of other types. This means that for reset of this magnetic system a slight reduction of current in the coil is required; in other words this magnetic system has a very high release ratio (a narrow loop on the characteristic, Figure 10.37).

The PT-40-type relay with a half-Z-shaped armature has similar positive properties, which is why it has been applied in industry and in the electric power industry for such a long time. In the PT-40-type relay, there is also an additional component on the common axle with a turning armature: a brake drum (7) (Figure 10.36c) with radial partitions filled with dry quartz sand. This component is a damper, reducing sharp acceleration of the movable system, vibration of contacts when they collide, and vibration of the armature caused by the alternating magnetic field. Vibration is extinguished by friction between the grains of sand.

Two relay windings can be connected to each other in series or parallel, thus allowing a change of the pick-up threshold of the relay by two times. The PT-40-type relay is produced for nominal currents from 0.2 to 200 A. The pick-up time of the relay does not exceed 0.1 sec at $1.2I_N$ current and 0.03 sec at $3I_N$ current. For application at currents protractedly exceeding pick-up current (up to $30I_N$), the relay must be supplied with an integrated saturating transformer, a diode bridge rectifier. This modification of the relay is called PT-40/1D.

As in the cases considered above PT-40 current relays also serve as the base for voltage relays (PH-51, PH-53), differing from PT-40 relays only by the winding. Separate coils in this relay allow creating on the basis of this construction a relay picking up from the difference of magnetic fluxes created by the currents in the relay coils. In the PH-55-type

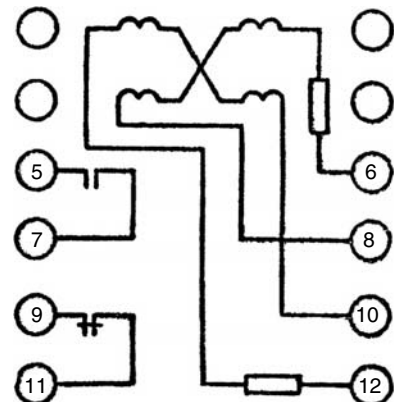


FIGURE 10.40

Circuit diagram of PH-55-type relay.

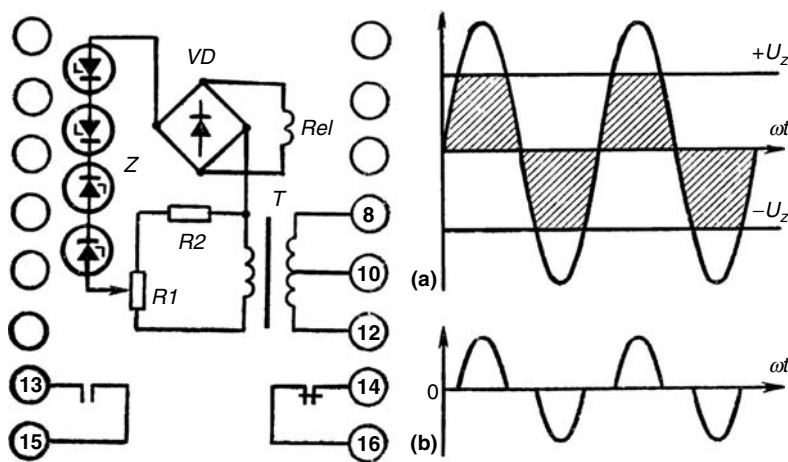


FIGURE 10.41
PH-58 type voltage relay with increased release ratio, produced on the basis of the magnetic system of the PT-40 relay. (a) — voltage form on Zener diodes Z; (b) — voltage on the input of the rectifier VD.

relay of synchronism control (Figure 10.40), each coil has two insulated half-windings with equal total section of wire copper.

The lower winding of one of the coils is linked with the upper half-winding of the other coil. Such linking allows us to obtain two insulated windings with strictly equal parameters, and a coupling coefficient between the windings, approximating 1. Each of the windings is connected to one of the synchronized voltages through the additional resistor. Resistances, the number of turns of the windings and the polarity of their connection are chosen in such a way that when nominal voltages coinciding by phase are applied to both windings, the total magnetic flux created by the windings will be full compensate and there will be no electromagnetic torque in the movable system of the relay. When vectors of synchronized voltages diverge, or one of them decreases, the total magnetic field will be unbalance and the relay picks up.

For the cases when a voltage relay with an increased release ratio (0.85 to 0.9) is needed, the winding of this relay is connected to Zener diodes (Figure 10.41). The pick-up

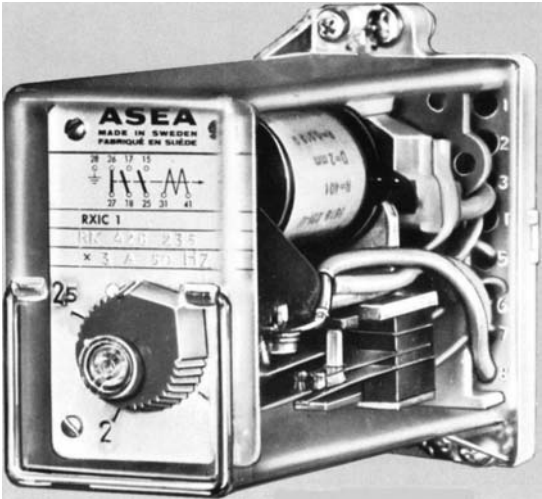


FIGURE 10.42
Instantaneous electromagnetic over-current (RXIC1) and overvoltage (RXC1) relay, produced by ASEA (ABB) from the year 1970. (ABB Relay Units and Components. Buyer's Guide, 1990.)

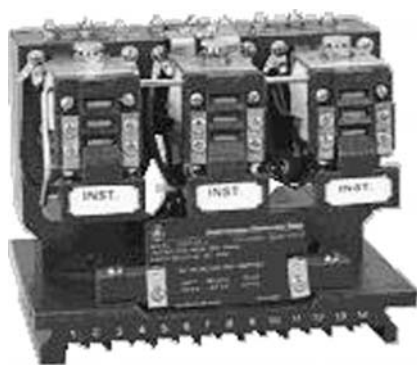


FIGURE 10.43

Instantaneous current relay of the HFC type with a clapper armature (General Electric).

threshold of the relay is adjusted with the help of a potentiometer (R1) supplied with a scale.

Simple instantaneous current and voltage relays were also produced on the basis of electromagnetic relays with a clapper armature (Figure 10.42). The pick-up threshold was adjusted in such relays by changing the spring stretch. Current relays were produced for nominal currents from 0.05 to 50 A, and voltage relays—for nominal values from 5 to 200 V. The size of the relay is $67 \times 41 \times 135$ mm. General Electric is still producing relays of such type (Figure 10.43). The HFC relay is a group of three independent relays equipped with a latch and a pointer flag.

It should be noted that relays of clapper type used as current relays have simpler constructions than relays with a turning armature (like PT-40), but they do not work as well when ratios of overload current are not enough. When current gradually increases in the relay winding and its value approximates the pick-up current value, the armature of such relays begins vibrating too much.

Large power relays with pick-up currents up to 630 A have the same constructive scheme (Figure 10.44). The REV-800 relay is designed for work in DC circuits. Nominal pick-up currents of different types of relays vary from 1.6 to 630 A. The pick-up threshold is adjusted by changing the tightness of the restorable spring. The size of the relay is $155 \times 190 \times 180$ mm, and the weight is 3.5 kg.

Relays with similar constructions are also produced for work in AC circuits with nominal pick-up currents of up to 1500 A. Such relays belong to the so-called “primary” (see above)

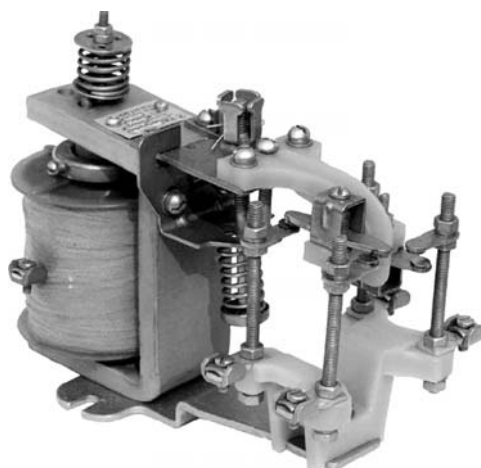


FIGURE 10.44

Power open electromagnetic current relay, REV-800, with a clapper armature (Russia).

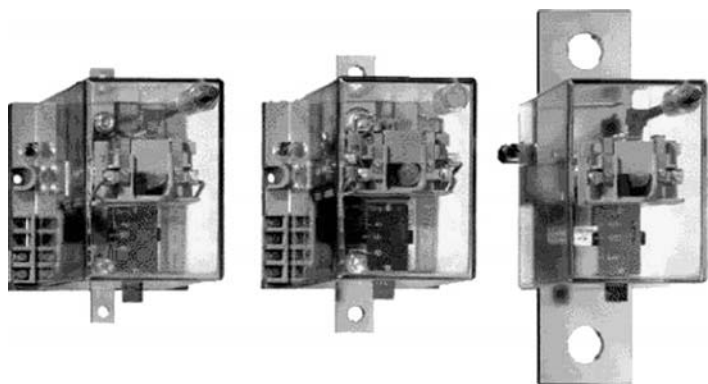


FIGURE 10.45
Primary instantaneous DC relays (Elektroba AG, Switzerland).

class of relays, which are switched to the circuit of high current directly, without auxiliary CTs. It should be noted that the percentage of primary relays with regard to the total number of produced relays is quite small, but nevertheless some companies continue producing such relays, mostly for DC circuits where it is impossible to use CTs (Figure 10.45). Different variants of these relays have pick-up currents from 1 to 6000 A. Pick-up time does not exceed 10 msec and the error is $\pm 5\%$ from setting. The magnetic system consists of a U-shaped iron with a hinged-armature. The latter actuates the contacts. The relays can be equipped with a mechanical latch and indicator flag, which can be reset by a button.

Relays of similar construction, designed for protection of DC and AC circuits, are produced by Siemens (Figure 10.46). The 3UG1 instantaneous electromagnetic over-current relay (Figure 10.46) consists of a high-armature magnetic system mounted on a moulded plastic base, together with a single-pole auxiliary switch.

With currents below the operating value, the armature is held in the rest position by a spring. Given an overcurrent equal to the preset value, the armature is instantaneously attracted and the auxiliary switch actuated. The armature returns to its rest position once the overcurrent has dropped to less than 50% of the lowest setting.

Automatic switches with an electromagnetic trip (without a thermal bimetal element) also belong to protective instantaneous current relays (Figure 10.47). Such relays cannot be used for protection from overloading because they do not contain bimetal elements with a

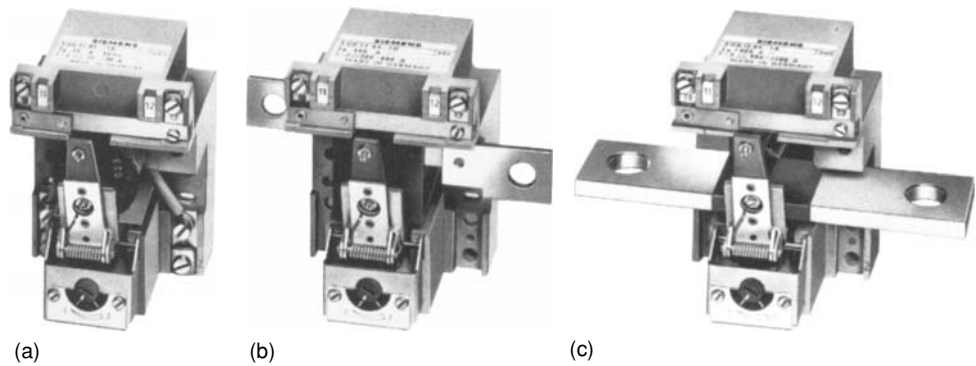


FIGURE 10.46
Single-pole primary instantaneous DC and AC relays of the 3UG1 type for currents 0.4 to 1300 A (Siemens catalogs).

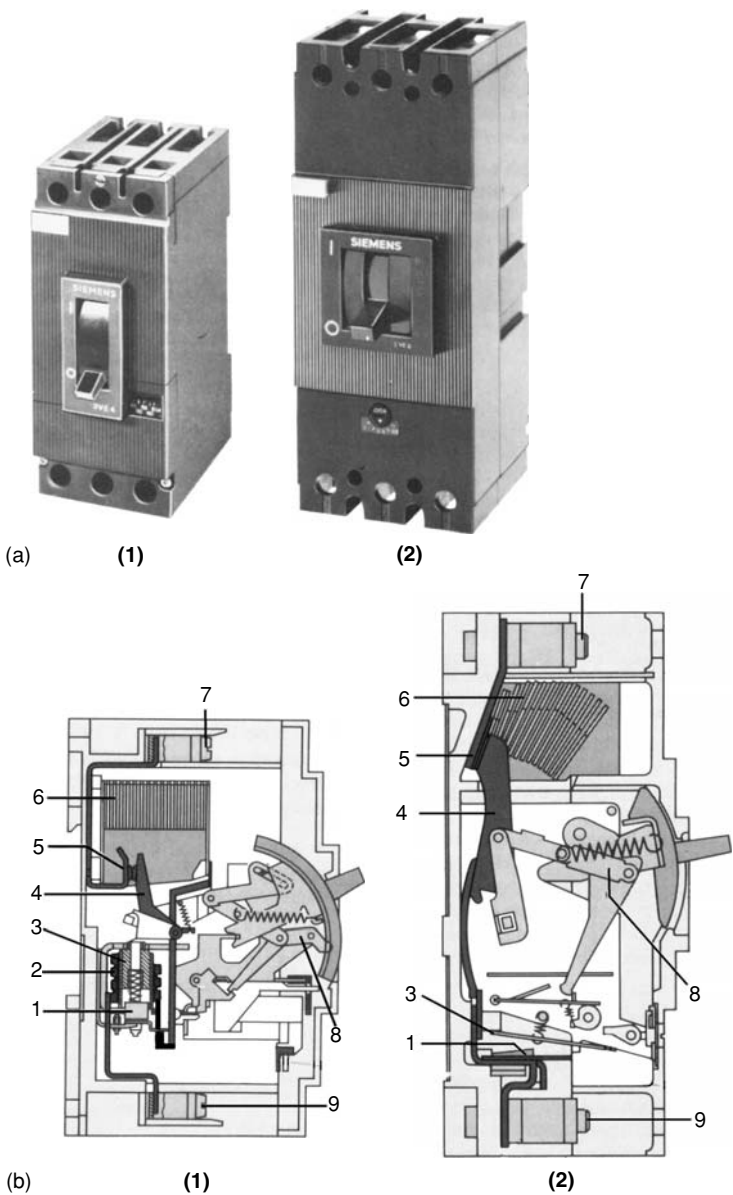


FIGURE 10.47
(a) Automatic circuit-breakers of the 3VN4 and 3VN6 types (Siemens). (b) Construction of automatic-circuit-breakers 3VN4 (1) and 3VN6 (2), with electromagnetic trips of the solenoid type (1) and the clapper type (2) armature. 1 — Instantaneous electromagnetic over current release; 2 — coil; 3 — armature; 4 — moving contact; 5 — fixed contact; 6 — arc quenching device; 7 and 9 — screws for fixing of external conductors; 8 — breaker mechanism. (Siemens catalogs).

TD dependent on current. The main function of these relays is instantaneous switching off of short-circuit currents with high ratios (5 to 20) with respect to the nominal current.

Like in the case of thermal relays, there are a lot of constructions of such instantaneous current relays, but their basic elements are the same: a current coil (or a portion of a bus bar for strong currents) connected in series with the protected load; a retractable (solenoid) or clapper armature, a spring, a trip mechanism and a contact system with an arc-suppressing unit.

10.3.2 Electronic Current and Voltage Relays

In the 1970s many key international companies developed electronic protective relays (Figure 10.48a and b) while continuing active production of electromechanical relays.

The printed circuit board, with cheap electronic components installed on the board and soldered by fully automatic systems functioning without man’s control, was considered to be more progressive and cheaper for production than precision electromechanical units of manual assemblage and adjustment. Other difficulties for the user, for example the need to locate malfunctions in electronic relays, the ways of repairing them, resistance of relays to overloads, overvoltages and interferences — all of these inevitable concomitants of electric networks, were not taken into account.

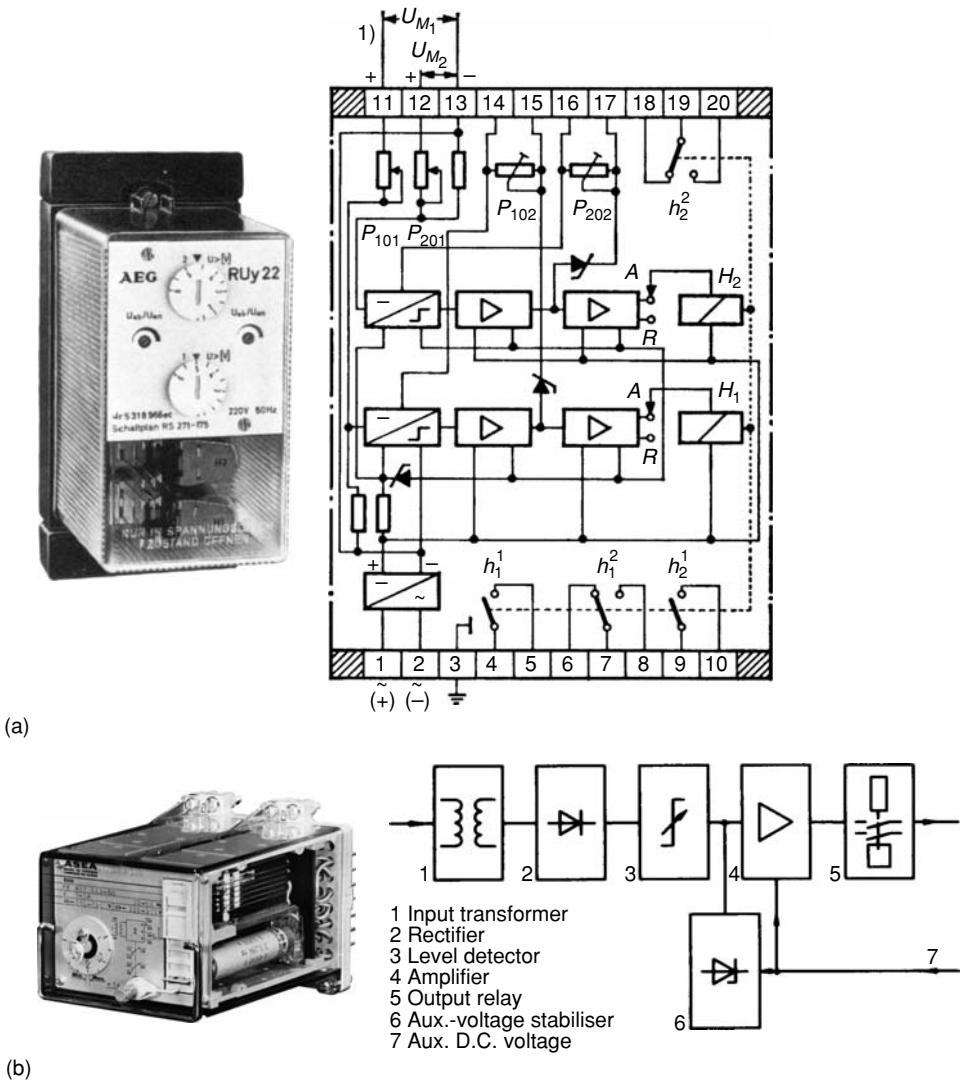


FIGURE 10.48
(a) Over-and undervoltage electronic relay of the RUy22 type (1974, AEG). (AEG Mebrelais Schutzrelais Reglar Elektrischer Groben 1975). (b) Electronic instantaneous over and undercurrent relay RXIG-2 type (1982, ASEA). (ABB Relay Units and Components. Buyer's Guide, 1990.)

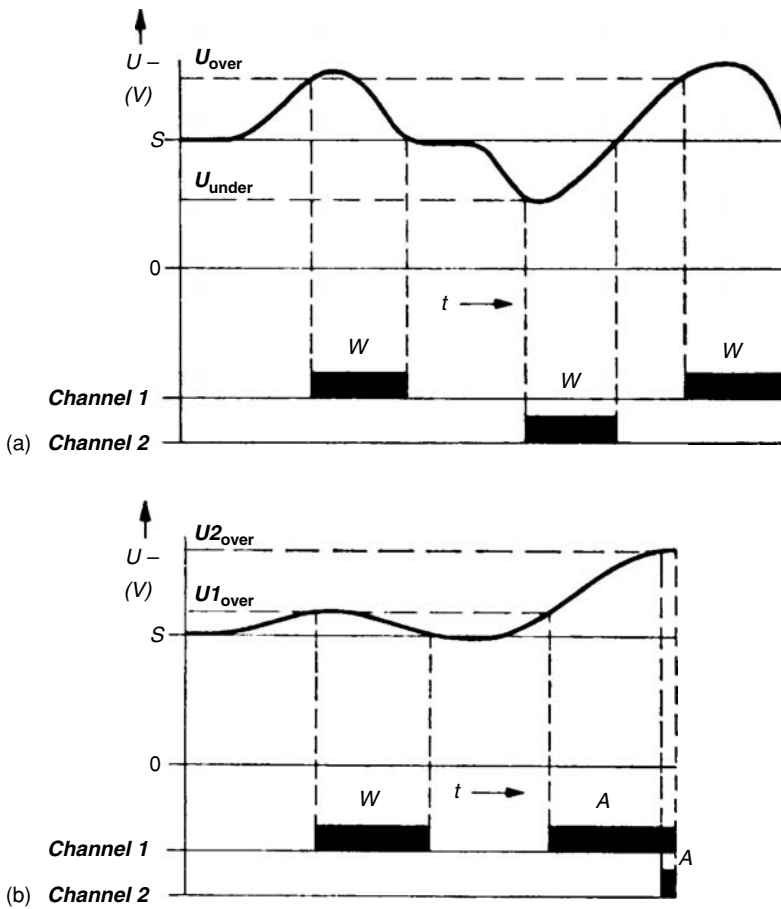
**FIGURE 10.49**

Diagram of function of a two-channel electronic current (voltage) relay. (a) Relay controlling the over-and undervalue. (b) relay controlling the two-stage overvalue.

As a rule, such relays contained an electronic measuring body in which the input values (current or voltage) were converted to low-level voltage, proportional to the input value and compared by level with the voltage on the electronic reference element. If the measured voltage is higher (or lower) than the reference voltage, a signal appears at the output of the compared element. It is amplified by an electronic amplifier and is applied to the winding of the electromagnetic output relay.

Simple types of such relays contained one channel with described elements, and more complex ones — two similar channels (like the RUy22-type relay produced by AEG — Figure 10.49). In earlier relay constructions, these channels had very simple circuits with two to three transistors, with a reference element on a Zener diode D1 (Figure 10.50). The ASEA Company produced RXIK-1-type relays based on similar principles of operation and made as a separate construction (Figure 10.51); however, they contained neither an individual output point electromagnetic relay nor the power source required for relay operation. This was a separate module which could work only with other modules containing the missing components, which well fit the concept of modular construction of relay protection systems, "COMBIFLEX," actively developed by the ASEA at that time.

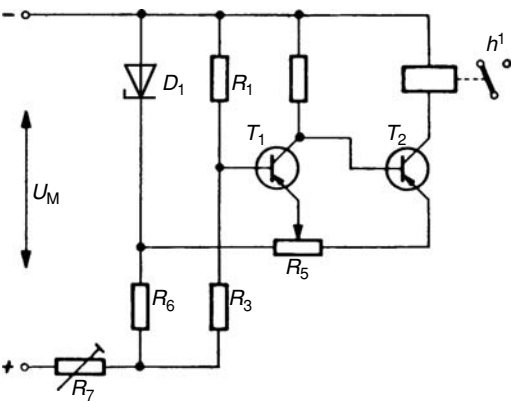
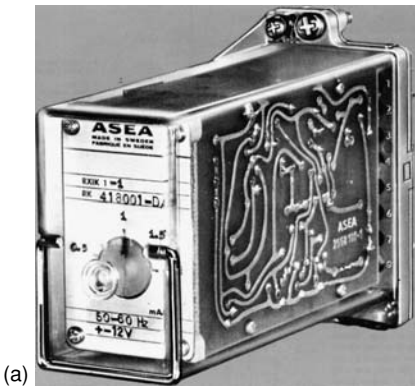
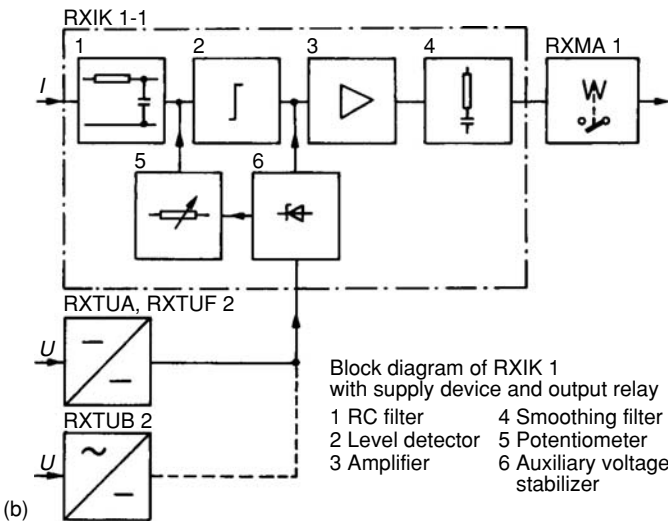


FIGURE 10.50
Circuit diagram of one channel of an RUy22-type relay (AEG).



(a)



(b)

FIGURE 10.51
RXIK-1-type modular relay containing only an electric transducer in its case (1974, ASEA). (ABB Buyer's Guide, 1990.)

According to this concept, the company did not aim at producing a protective relay with complex functions as a whole, but rather built such complex protective systems out of separate simple relay-“blocks.” Perhaps that idea was right in 1970s, but it proved to be a failure when units of miniature specialized processors, capable of functioning as a cupboard full of such COMBIFLEX “units,” began to appear.

The main drawbacks of the so-called “static” electronic relays based on this principle, were limited sensitivity to changing of the input signal, and a not very high release ratio (0.7 to 0.8), caused by hysteresis of the Zener diode.

The so-called dynamic relays are free from this drawback. They have appeared recently and have practically replaced semiconductor static relays in protective systems. The general principle of functioning of such relays is that during operation, a special threshold circuit (a comparator, a univibrator, or a trigger) is switched ON every half-period, when the amplitude of the input current (voltage) reaches the value equaling the reference voltage, and returns to its initial position (switched OFF) when the sinusoid of the input current (voltage) passes through the zero value, or when the input signal changes its polarity (Figure 10.52). Thus during the whole period when the affecting input value exceeds the prescribed level, the sensitive element of the relay is automatically switched from one mode to another, synchronously with the sinusoid of the controlled current. To rule out the possibility of influence of signal oscillations on the stability of the state of the output unit, a pulse stretcher (or an integrator) is used. It is based on a capacitor charging

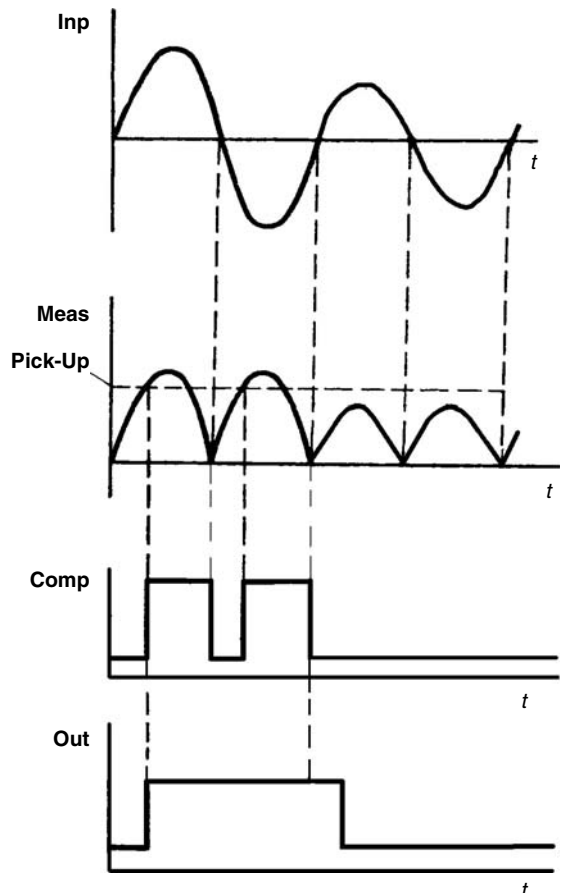


FIGURE 10.52

Simplified diagram of the function of an electronic relay of the dynamic type. **Inp** — input value (current, voltage); **Meas** — measured voltage obtained by rectification and proportional transformation of the input value; **Pick-Up** — comparator pick-up threshold; **Comp** — voltage at the output of the comparator; **Out** — output voltage of the electronic circuit.

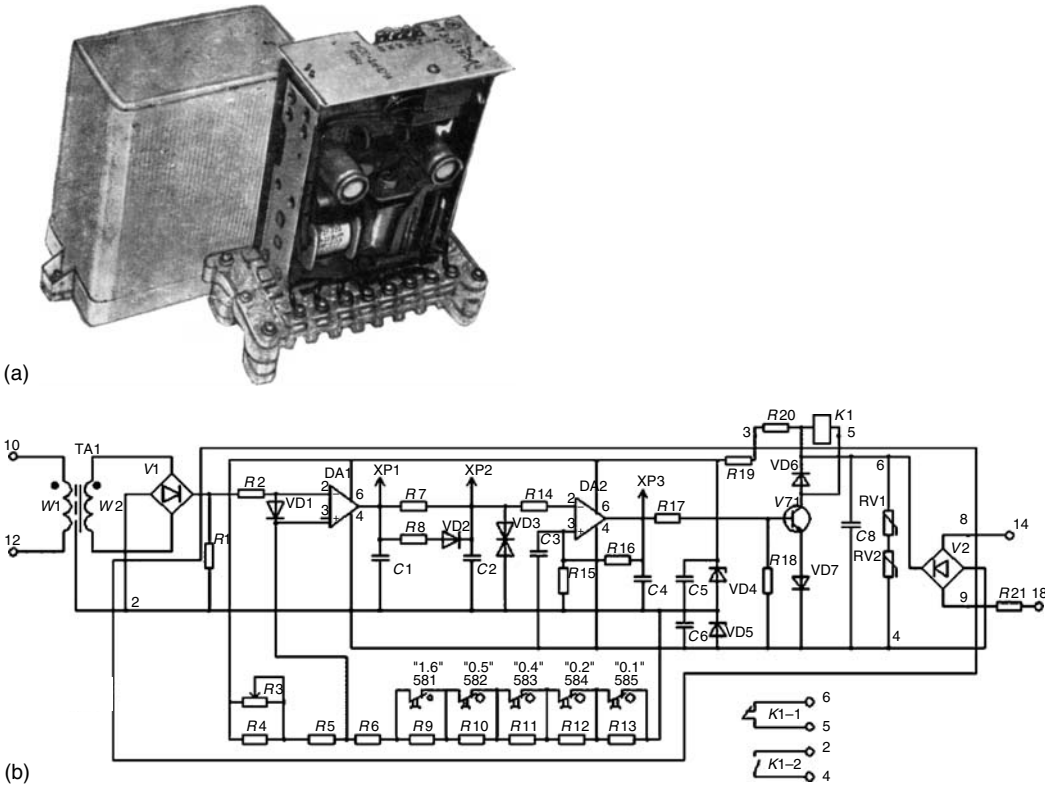


FIGURE 10.53
(a) Dynamic semiconductor current relay of the RCT type (1990, Russia). (b) Circuit diagram of universal relay RCT-type (for current) and RCH-type (for voltage).

during the ON-state of the threshold circuit and maintaining the output element in the ON-state during the pause between pulses. To increase noise-immunity of the relay, an RC-circuit is cutting between the comparator and the output amplifier. It delayed picking up of the output unit up to a few tens of milliseconds. If the high level input signal is of short duration, which is typical of noise, the output unit will not have time to pick up during the noise.

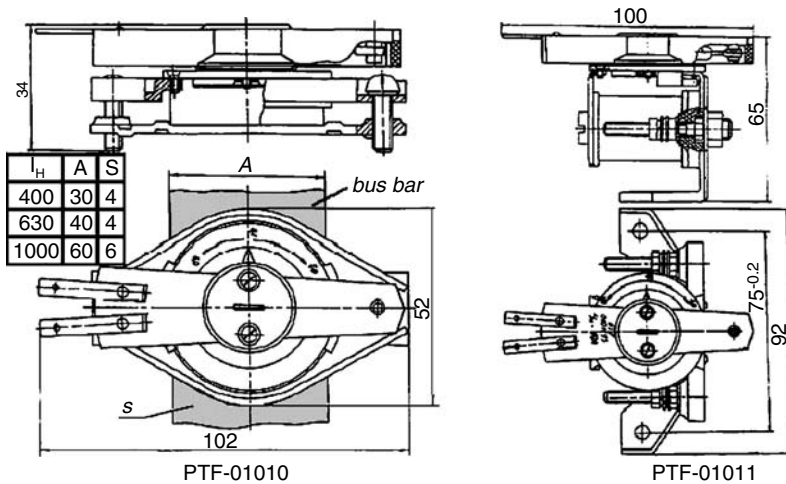
The release ratio of this circuit equals 1, since the relay returns to its initial position every time the amplitude of the sinusoid of the controlled current is not sufficient for repeated (during each half-period) starting of the threshold element. This has nothing to do with the hysteresis of elements of the circuit.

One can adjust the pick-up threshold of the relay by changing the reference voltage value with the help of a potentiometer. Practically all electronic current and voltage relays produced in 1980–90's on, are based on a similar principle (Figure 10.53).

10.3.3 Reed Switch Current Relays

For construction of instantaneous overcurrent and overvoltage relays reed switches were also used, although not so widely as relays of the types mentioned above.

According to the information we have, the simplest reed switch current relays (Figure 10.54) were produced only in the former U.S.S.R., and are still produced in Russia. These are simple constructions containing a large reed switch installed with a possibility

**FIGURE 10.54**

Reed switch current relays with a bus bar section, and with a coil. Sizes of bus bar are shown in the table (to the left).

of turning on the bus bar section or on the coil. As the reed switch turned relatively of magnetic field supply (bus bar or coil), its sensitivity to the magnetic field of current passing through the bus bar or the coil changed (see [Figure 5.76](#)). Such relays are designed for work in DC circuits only.

Nominal values of currents for different modifications of these relays lie within 400 to 1000 A (with bus bar) and from 1.6 to 250 A with coil. A series of protective hybrid (reed-electronic) current relays was designed by the author of this book in the 1980–90's, and was put into production under his direction. These relays are still produced in the Ukraine under the brand "Quasitron" by a private company, "Inventor" (Kharkov).

The "Quasitron" is a multipurpose protection relay based on a hybrid (reed-electronic) technology, with very high noise immunity ([Figure 10.55a](#)). A current sensor may be mounted into the relay unit (as shown in [Figure 10.55a](#)) or mounted outside the relay unit on an additional plate ([Figure 10.55d](#)). One relay unit may be used simultaneously with several different types of current sensors, each of which has a different current pick-up value.

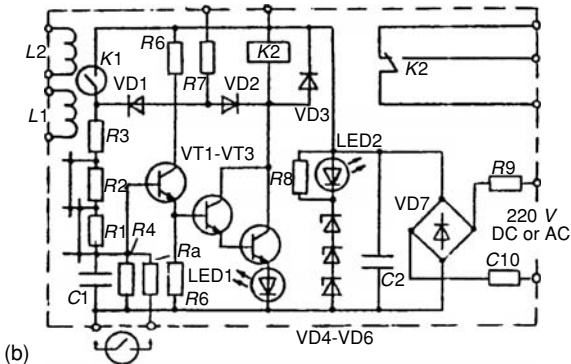
All sensor outputs are connected to the relay unit via low-voltage wires. The relay unit has three time–current characteristics (T1–T3) ([Figure 10.56](#)), one of which can be selected by a customer by means of jumpers on resistors R1, R2 (see [Figure 10.55b](#)). For this purpose one (or two) jumper(s) may be cutting.

As the circuit configuration ([Figure 10.55b](#)) becomes simpler, it does not contain ICs; its active solid-state components (transistors) do not constitute a threshold element and are merely used as a simple amplifier. An interface between the electronic circuit and the outside network bus is implemented via an insulated interface, based on a reed switch (K1), which also plays the role of threshold elements and starts vibrating with double network frequency when the relay picks-up. The contact erosion-free capacity of the reed switch (about 10^6 to 10^8 operations) along with the short period of the maximum current relay's ON-state ensures the required commutation resource of the relay.

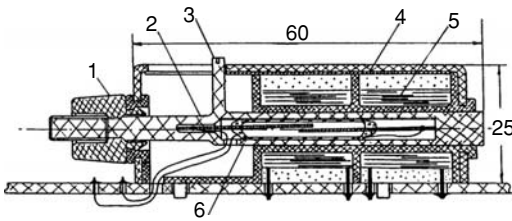
The amplifying module of the base circuit is nothing more than a compatibility link between the integrating couple (L1–L2C1), and the output auxiliary relay (K2) provides



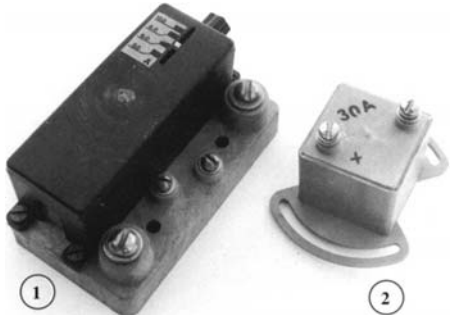
(a)



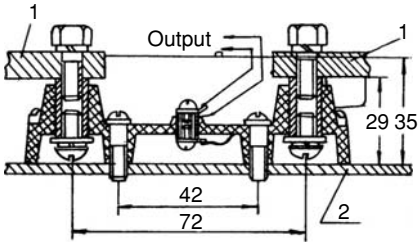
(b)



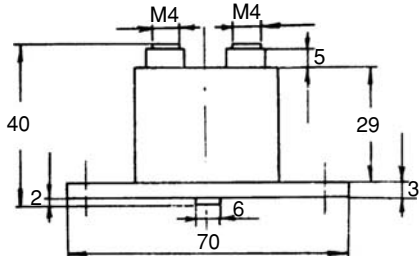
(c)



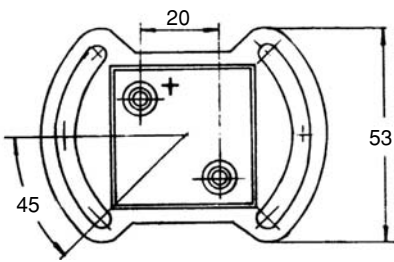
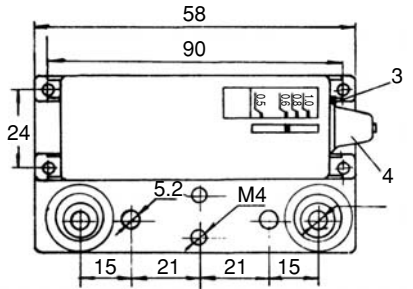
(d)



(e)



(f)



(Continues)

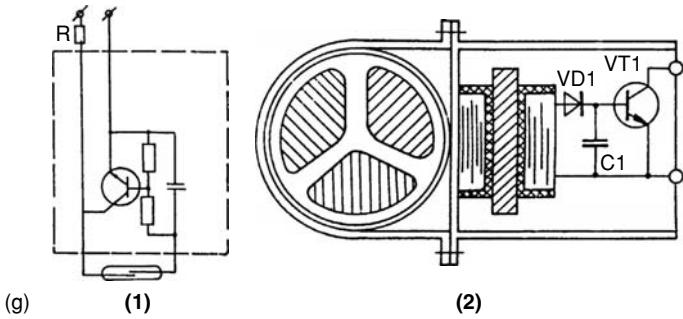


FIGURE 10.55 (Continued)

(a) Hybrid over-current protection relay of the “Quasitron” series (without protection lid). (b) Circuit diagram of “Quasitron” relay. K1 — Reed switch; L1, L2 — input current coils; K2 — output auxiliary relay. (c) A “Quasitron” imbedded current sensor, with adjustable current trip level. 1 — Limb; 2 — movable dielectric capsule; 3 - level indicator of current pickup; 4 — ferromagnetic screen; 5 — coil; 6 — reed switch. (d) External low voltage current sensors for “Quasitron” relays. 1 — Cutting-circuit sensor type 1 for current pick-up 0.01 to 100 A; 2 — sensor type 2 for bus bar and cable installation (30 to 5000 A). (e) Outside dimensions of external low voltage current sensor, Type 1. 1 — External wires of current circuit; 2 — plate; 3 — fixative element; 4 — limb; “output” is connected to relay unit. (f) Outside dimensions of sensor type 2 for bus bar and cable installation. (g) Circuit diagrams of type 2 sensors. 1 — for current level 100 A and more; 2 — for low current levels.

for the stability of the ON-state of the relay under the K1 (reed switch) vibration conditions.

The “Quasitron” is a relay of the dynamic type (see above), with a high release ratio (0.85 to 0.95). This is caused by the algorithm of its operation: return of the relay to the initial position is not connected with hysteresis of the reed switch, as it follows the current sinusoid and switched OFF forcedly every half-period. This is perhaps the only one type of electro-mechanic relay (the reed switch is an electro-mechanical element) capable of working in the dynamic mode peculiar to electronic relays. The high frequency and short pulse interference at the relay input cannot migrate to the electronic module since K1, being the interface link, does not react to the high frequency control signals due to the inherent inertia. Neither does it respond to the transient interference from the power circuit commutation, therefore the whole relay becomes very robust to power circuit pulse interference. The effect of the magnetic component of the dissipation fields can be

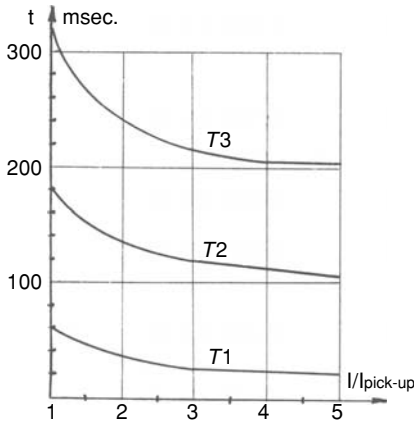


FIGURE 10.56

Time-current characteristics of “Quasitron” relay.

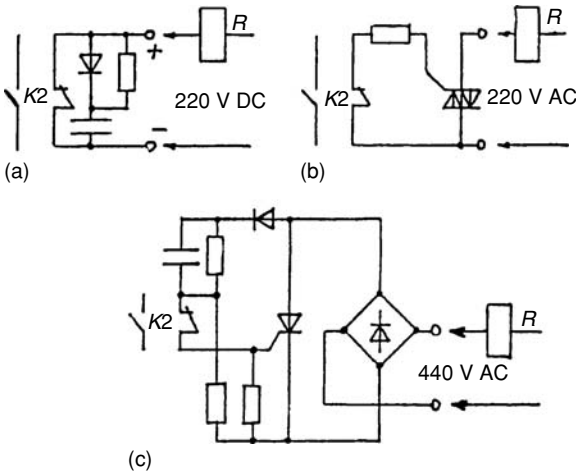


FIGURE 10.57
Output modules for “Quasitron” relay. (a) With spark protection, for DC load with large inductance; (b) with power amplifier, for power AC load (up to 500 VA); (c) for AC load, connected to power supply with voltage more than switching voltage of output auxiliary relay. K2 — contact of output auxiliary relay, mounted on PCB in relay unit; R — load of resistive or resistive-inductive type.

neutralized by introducing a ferromagnetic screen into the relay design (see Figure 10.55c). This 1.5 mm screen shields the reed switch in the fields with an intensity much higher than that of the dissipation fields under actual operating conditions.

For different applications of the “Quasitron” device several types of output modules are available (Figure 10.57). For “Quasitron” relays not only were low-voltage current sensors designed, but also high-voltage current sensors that can be installed directly onto the high-voltage line without CTs (Figure 10.58). Without a doubt, one advantage of this sensor is its compactness and the possibility of direct installation on the high-voltage wire. This is important from the point of view of cost reduction of high-voltage equipment, and from the point of view of minimization of compact distributing devices of the cabinet type. On the other hand, that compactness and the lack of necessity for high-

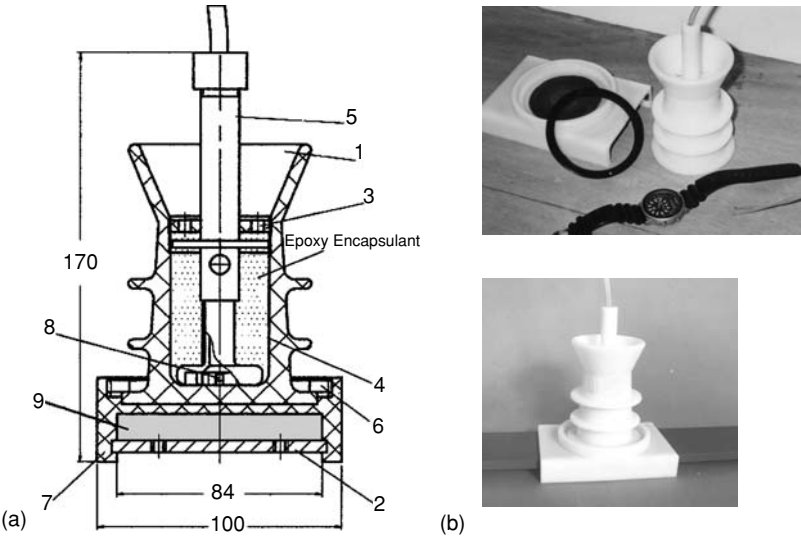
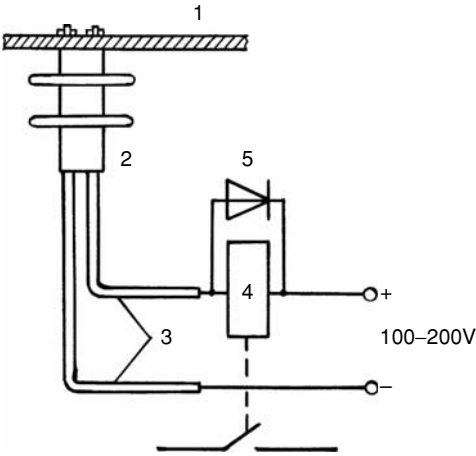


FIGURE 10.58
(a) Construction of the high-voltage current sensor of the “Quasitron” relay. 1 — Main insulator; 2 — fixative plate; 3 — inside nut; 4 — semiconductive cover; 5 — bushing; 6 — fixative nut; 7 — fastener; 8 — reed switch; 9 — bus bar. (b) External design of the high-voltage current sensor of the “Quasitron” relay.

FIGURE 10.59
Principle of application of a single AC relay with high-voltage insulation. 1 — Conductor line; 2 — relay; 3 — high-voltage wire; 4 — low-voltage auxiliary relay; 5 — diode.



voltage CT applications do not allow modernization of existing compact distributing devices, since there no place for an additional CT was envisaged.

Entire independence on the one hand and full compatibility on the other hand allow the relay to provide complex protection simultaneously of all circuits (both low-and high-voltage ones, with different current settings) of the complex electrical installation with the help of only one “Quasitron” relay unit.

In the case of a single AC relay when picking up excess of a given setting in the high-voltage circuit and switching of the auxiliary relay of the low-voltage circuit (Figure 10.59) is required, it is possible to use a high-voltage sensor with an integrated electronic filter, transforming the reed switch vibration at its pick-up to a standard signal of the “ON-OFF” type (Figure 10.60).

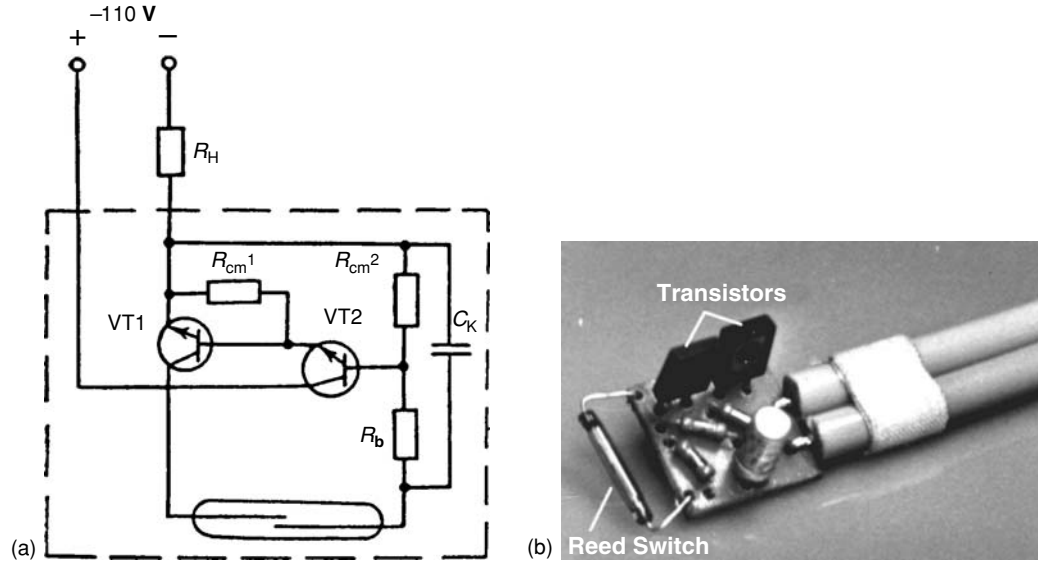


FIGURE 10.60
Electronic filter integrated to the high-voltage current sensor. After the sensor has been assembled, all inner space is filled with epoxy resin.

10.4 Current Relays with Independent “Time-Delays”

10.4.1 Relays with Integrated Clockwork

When protective relays began to be used in the power industry it became clear that just instantaneous relays are not enough for effective protection. As mentioned above, only a set of relays with different and at the same time matched pick-up currents, and different TDs, can provide selectivity of protection on long power lines.

Already at the beginning of the last century direct-action relays (that is relays directly affecting the driving gear of the switching apparatus), with the simplest integrated clockwork providing the required TD, were produced (Figure 10.61). The pick-up time of such a relay is determined by the balance of three constituents: power of attraction of the armature to the core, opposing force of the spring, and the position of the lower end of the spring depending on the anchor clockwork.

The Anchor mechanism (anchor) (Figure 10.62) consists of an anchor wheel, a fork, and a balance (double pendulum) — the part of the clockwork transforming energy from the main part of the driving wheel (in clocks — a spring) to pulses transmitted to the balance to maintain a strictly determined oscillation period necessary for uniform rotation of the pinion mechanism.

The principle ideas of such mechanisms were laid already in the 17th century, but its modern design derives from efforts in the 18th and 19th centuries of many watchmakers, the especially distinguished ones being Abraham-Lui Breget and Jorge Leshaut. Even the famous playwright Pierre Ogusten Bomarschet turned his attention to improvement of this mechanism — the main clock unit, determining its accuracy.

When the running torque affects this mechanism from the direction of the driving wheel, the anchor fork (3) moves the teeth of the anchor wheel (4) one by one at a certain speed that

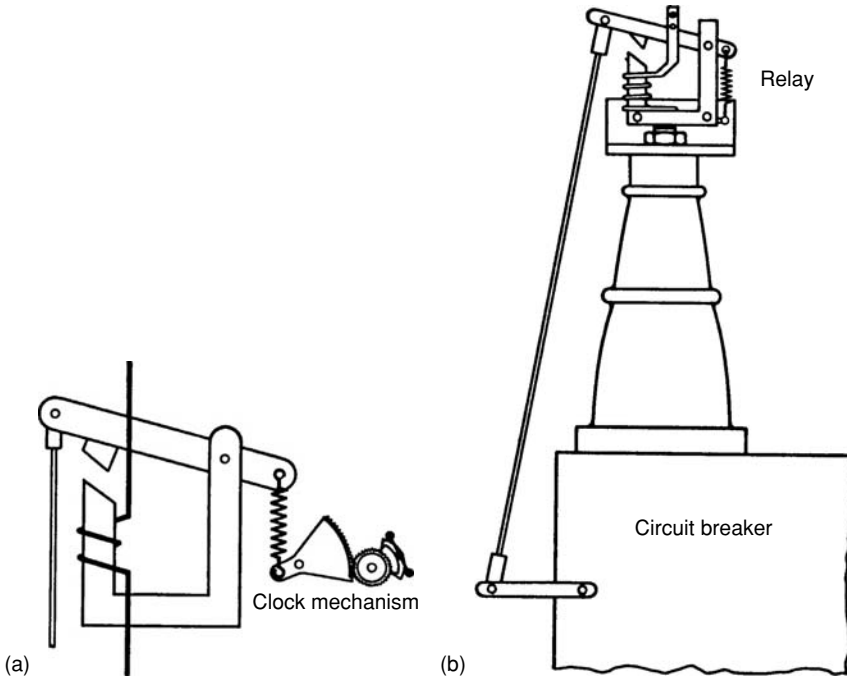
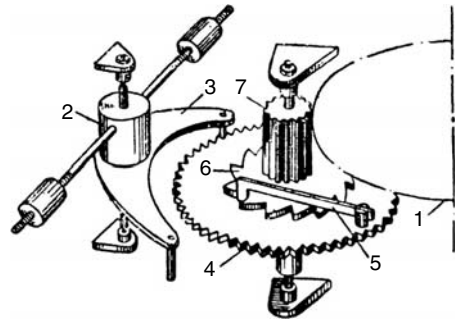


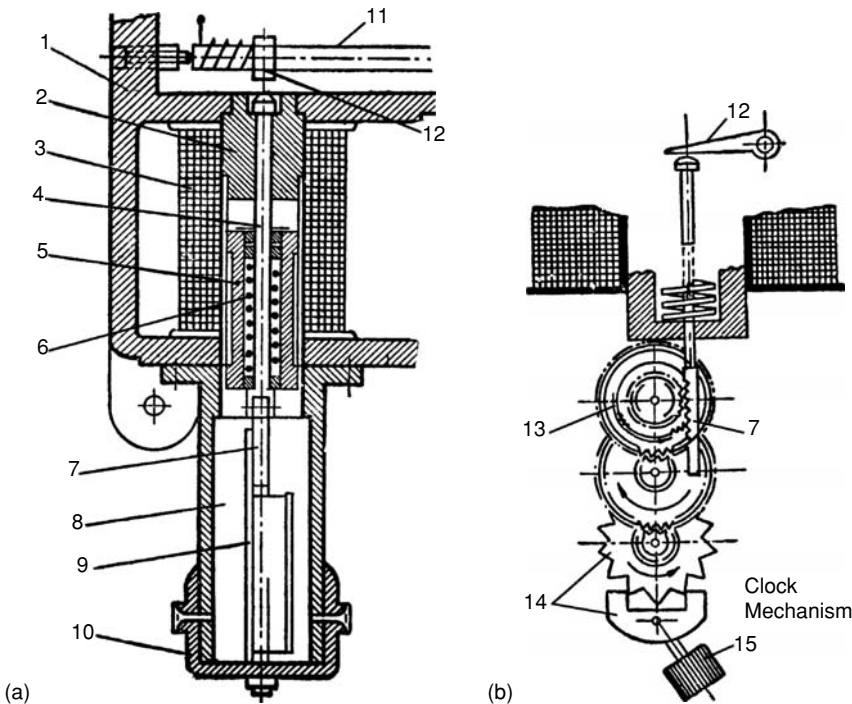
FIGURE 10.61
Protective direct-action current relay with an integrated anchor clockwork.

FIGURE 10.62

Anchor clockwork. 1 — Driving wheel; 2 — balance-wheel; 3 — anchor fork; 4 — ratchet spring; 5 — ratchet-wheel; 6 — pinion.



does not depend (much) on the running torque. In this relay, shown in Figure 10.61, the spring was selected in such a way that the electromagnetic torque developed by the coil was enough for full overcoming of its resistance at high current ratios only (more than 2 to 3). In this case, the armature overcame the resistance of the spring and was immediately attracted to the pole of the magnetic core before the clockwork started operating. At currents in the coil equaling 1.1 to 1.5 of the nominal value the armature began moving but the relay was not activated because of increasing resistance of the spring. The lower end of the spring activates the anchor mechanism which slowly releases the lower end of the spring by reducing its tension and allowing the armature to go on moving. The speed of the lower end of the spring is constant and does not depend much on the tautness of the spring. Obviously, when initial current is strong in the relay winding, the degree of the initial

**FIGURE 10.63**

KAM-type direct-action current relay with an integrated clockwork (1937, "Elektroapparat" plant, Russia). 1 — Magnetic core; 2 — stopper; 3 — current coil; 4 — striker-pin; 5 — retractable armature (hollow cylinder); 6 — spring; 7 — rack; 8 — space for the clockwork; 9 — clockwork; 10 — cover; 11 — breaking shaft; 12 — rod of the breaking shaft; 13 — ratchet-wheel; 14 — anchor mechanism; 15 — pendulum.

tension of the spring will be greater and the armature will move closer to the pole of the magnetic core. This means that at high current the armature has less travel to its final position which is why the time of operation of the anchor mechanism, releasing the end of the spring at a constant speed, will be less, meaning that the TD of the relay (until its complete pick-up) will be less.

Relays with similar principles of operation (only not of clapper type, but with a retractable armature) were produced in the 1930s in the former U.S.S.R. by the Leningrad plant "Electroapparat" (Figure 10.63). In this relay when current equaling or exceeding setting current passes through the coil (3), the armature (5) starts going up into the coil and also carries the striker-pin (4) through the spring (6). As this pin is linked with the rack of the clockwork, it slows down movements of the armature in the upper direction, as in the example considered above. When the armature (5) reaches its extreme upper position, it turns the rod (12) of the shaft (11) with the help of the striker (4) and the shaft turns and releases the latch of the trip, thus putting into action the breaking mechanism of the switch. At high current ratios, the armature immediately reaches its top position and activates the breaking mechanism of the switch with the help of the striker-pin (4). Thus the relay has two areas on its time characteristic (Figure 10.64): a TD dependent on the current and a constant delay caused by mechanical displacement of construction elements.

The relay coil has several taps and by switching of them, one can choose one of the characteristics. In addition, by displacing the whole clockwork up or down of the rod (7) one can change the TD value of the clockwork. Release ratio of the relay in the dependent part of the characteristic equals 0.6 to 0.8, and for work in the independent part of the characteristic — 0.8 to 0.9. Minimal pick-up time in such construction of the relay is 0.7 sec in the independent part of the characteristic and almost 1 sec — in the dependent one. These are quite high values (several times higher than modern protective systems provide) for effective protection. The KAM relay was produced until 1940, when it was slightly modified and was produced commercially in the U.S.S.R. by several plants under the names RTB, RTM, and RMB. The problem of low performance remained in all of these relays.

Strange as it might seem, nowadays that computers and microprocessors are widely used in relay equipment, the RTB relay with its almost 70-year history (basically a KAM relay with an enhanced clockwork) is still produced toady, by the Repair Enterprise Lenenergo (St Petersburg, Russia).

Some current relays produced contain such a set of elements in their construction that it may be difficult to define to what class of relays they belong to. For example, the primary direct-action relay of the MUT-1 type (Figure 10.65) contains an integrated CT, an

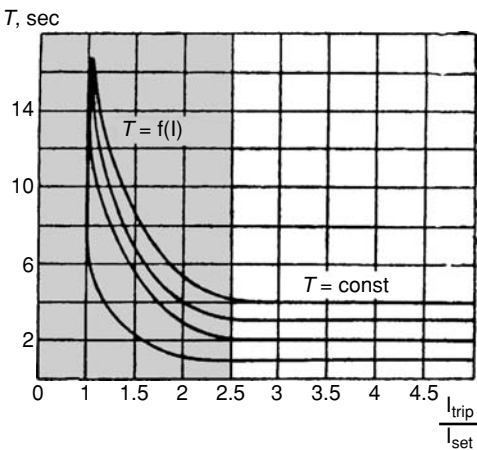
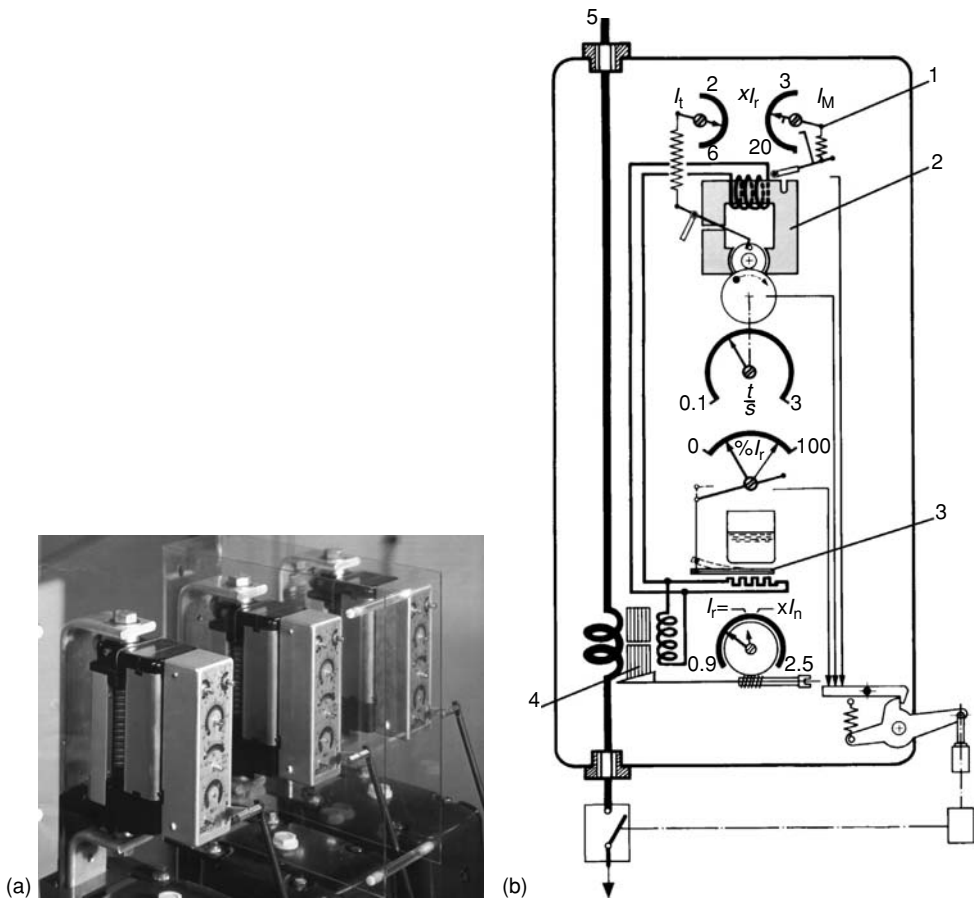


FIGURE 10.64

Time-current characteristics of a direct protection relay of the KAM type.

**FIGURE 10.65**

(a) Three primary direct-action current relays of MUT-1 type (Sprecher + Schuh). (b) Construction diagram of the combined primary direct-action current relay of the MUT-1 type. 1 — Electromagnetic instantaneous element with adjustable ratio of pick-up current; 2 — TD element (synchronous motor); 3 — bimetal element; 4 — integrated CT; 5 — conductor line.

instantaneous element, a TD element based on a synchronous motor, and a thermal (bimetal based) element. The nominal current of the MUT-1 relay lies within 1.5 to 300 A, the adjuster of current ratio of instantaneous cutoff — within 2 to 20, pick-up current of the thermal element — within 0.9 to 2.5 of the nominal current, and pick-up time of the thermal element — 15 to 120 min.

In the 1960–70's many leading companies produced indirect-action current relays with an integrated clockwork. A typical example of such a relay is the widespread RSZ 3gk type-relay, produced by AEG (Figure 10.66). The RSZ 3gk-type relay is quite a large and heavy device (its size is $342 \times 165 \times 152$ mm and its weight 6.8 kg), containing three current units with independent adjusting consisting of clockwork, three units with adjustable instantaneous pick-up thresholds and the clockwork itself (Figure 10.66a).

Current relays (or units of relays) with a TD are usually indicated by the symbol $I >$ and instantaneous relays (or units of relays) by the symbol $I \gg$. These symbols are quite logical and easily memorized. The former characterized the relay picks up at a current exceeding a certain value (as a rule this is a relay with a TD) and the latter characterized the relay picks up at a current much exceeding a preset value (this is a characteristic of instantaneous relays). Relays of maximum and minimum voltage are marked similarly ($U >$, $U <$).

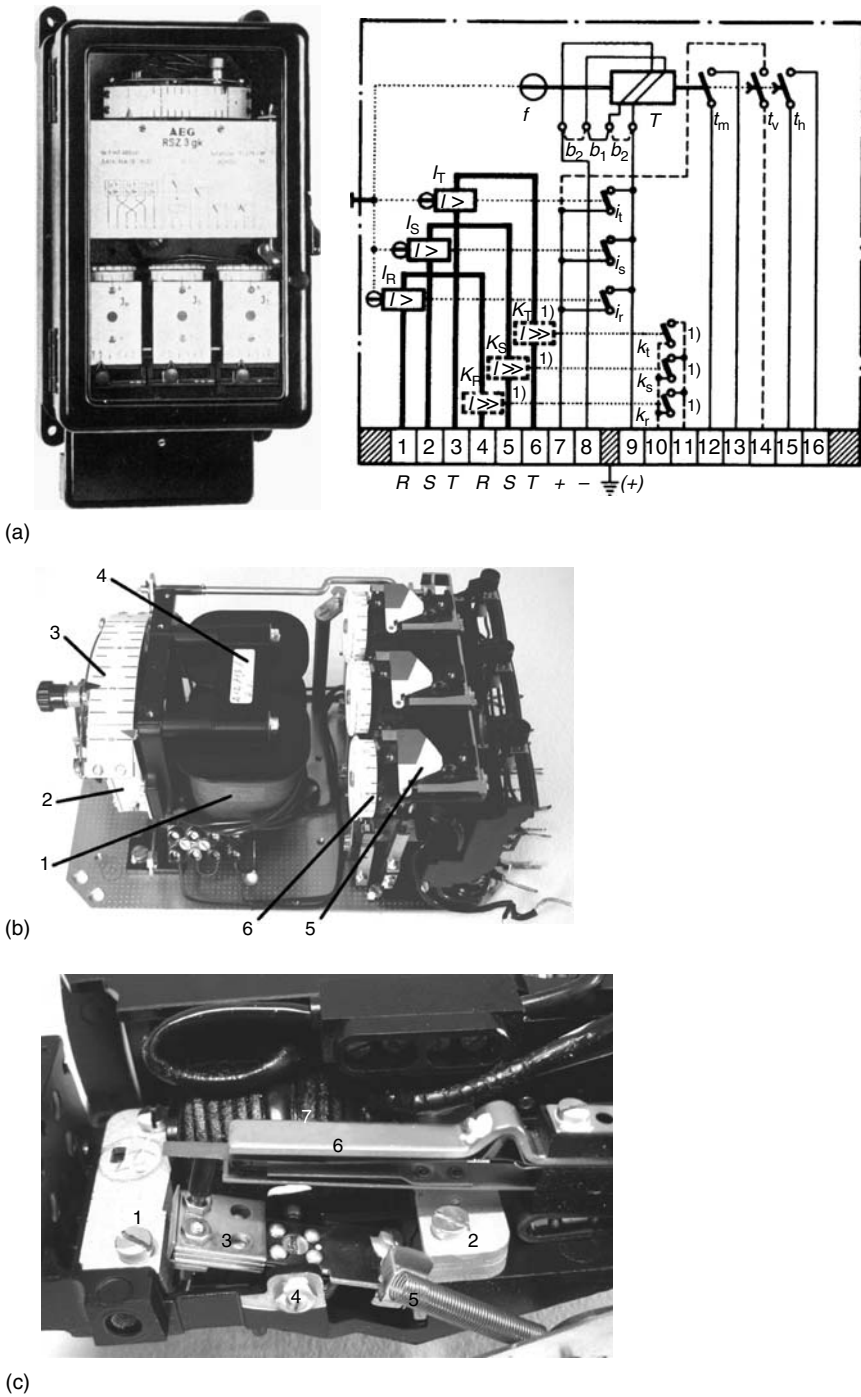


FIGURE 10.66
(a) Three-phase current relay of the RSZ 3gk type, with integrated clockwork (AEG, 1975). (b) RSZ 3gk relay construction. 1 — Coils of the electromagnet of the clockwork; 2 — clockwork; 3 — scale of the clockwork; 4 — magnetic core of the electromagnet; 5 — turning flag opening the red sector when the relay pick-ups; 6 — scale of adjustments of the current unit $I >$. (c) Magnetic system of a current unit $I >$, with a turning Z-shaped armature. 1 and 2 — Terminals of the Π -shaped magnetic core; 3 — Z-shaped turning armature; 4 — rotation axis of the armature; 5 — spring; 6 — contacts holder; 7 — coil.

(Continues)

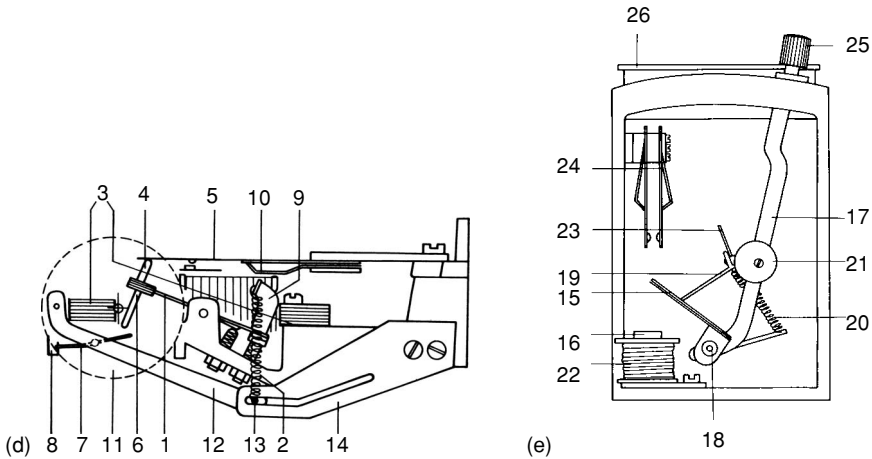


FIGURE 10.66 (Continued)

(d) Construction of the current unit $I>$. 1 — Turning armature; 2 — restorable spring; 3 — terminals of the Π -shaped magnetic core; 4 — contact pusher; 5 — movable contact; 6 — pusher of the position flag; 7 — intermediate flag pusher; 8 — prominent part of the flag; 9 — angle bar linking the armature with the spring; 10 — contact limiter; 11 — limb of pick-up current adjustment with a scale; 12 — tie-rod of adjusting element of the spring tension; 13 — moving element of the spring; 14 — post with a notch. (e) Construction of instantaneous unit ($I>>$) 15 — clapper type armature; 16 — pole of the core; 17 — pick-up threshold arm; 18 — rotation axis of the armature; 19 — lever; 20 — spring; 21 — eccentric disk for adjustment of the relay scale; 22 — coil; 23 — contacts pusher; 24 — contact system; 25 — lever handle for pick-up current adjustment; 26 — scale. (AEG 1975).

Such signs can be usually found on the relay itself, near the corresponding element of adjustment. They are also indicated on schemes, where the letters *R*, *S*, *T* (Figure 10.66a) are used to indicate the three phases of AC systems.

As can be seen from the scheme, when the current unit $I>$ picks up, it switches ON the electromagnet of the clockwork by its contacts, and the contacts of the current unit $I>>$ go out directly to the terminal block where they are used for switching of external circuits.

The magnetic system of the current unit $I>$ (Figure 10.66b) is constructed with a Z-shaped turning armature, which has been known and in use for more than 70 years now and which continues to give a good account of itself in current relays (the peculiarities of relays with such armatures were considered above).

The placement of the both current units, $I>$ and $I>>$, in constructions, are on both sides of the same plastic carcass, in the form of a common block. All these blocks, relating to all three phases, are installed on a common heelpiece. Unlike relays with a Z-shaped armature described above, which were supplied with a very soft spiral spring requiring protection from mechanical effects, in this construction quite a heavy coil spring of cylindrical shape is used and its power is transmitted to the armature with the help of a simple and reliable mechanical system, with the possibility of slide and regulation of its tension degree (Figure 10.66d).

To adjust the required pick-up current the limb (11) is turned and the proper section of its scale placed in front of the stationary pointer. When the limb turns the finite element of the spring (13) moves in the notch of the post (14) and the tension of the spring changes.

The instantaneous current unit $I>>$ works only under high current ratios and has a considerably simpler construction, of the clapper type (Figure 10.66e). When the lever (17) changes its position, the armature (15), together with the spring (20), turns, so the pick-up current is adjusted not by changing of the spring tension as in the previous case, but by the reducing of the air gap between the armature and the terminal of the magnetic core.

10.4.2 Current Relays with Electronic Time-Delay

As it can be seen from Figure 10.66d, the clockwork, together with the electromagnet, occupies half of the inner space of the relay. This is the heaviest element of the construction: it weighs about 2 kg. It is probably also worth mentioning that this is the most expensive unit of the relay. That is why it would be only natural to look for the solution to replace this unit with a semiconductor time unit.

This solution was accepted and production of the RSZ3yk-type current relays was arranged. These relays were very much like the relay considered above, except that the clockwork and the powerful electromagnet were replaced with a simple (and light) printed circuit board with an electronic time relay based on the RC-circuit and electronic amplifier, already well known to us (Figure 10.67b). Another difference of this relay from

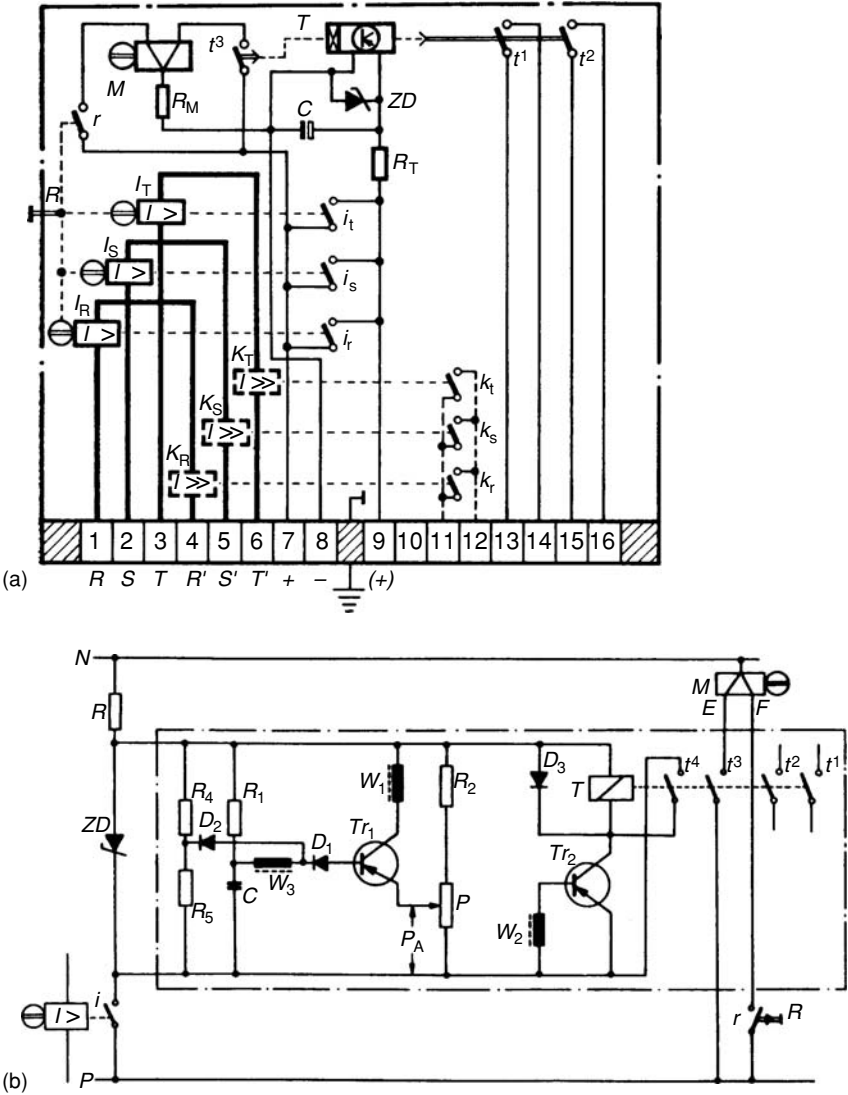


FIGURE 10.67 (a) RSZ3yk-type current relay with a semiconductor element of TD (T) instead of a mechanical one. Produced by AEG. (b) Circuit diagram of the TD element of the RSZ3yk-type current relay (AEG 1975).

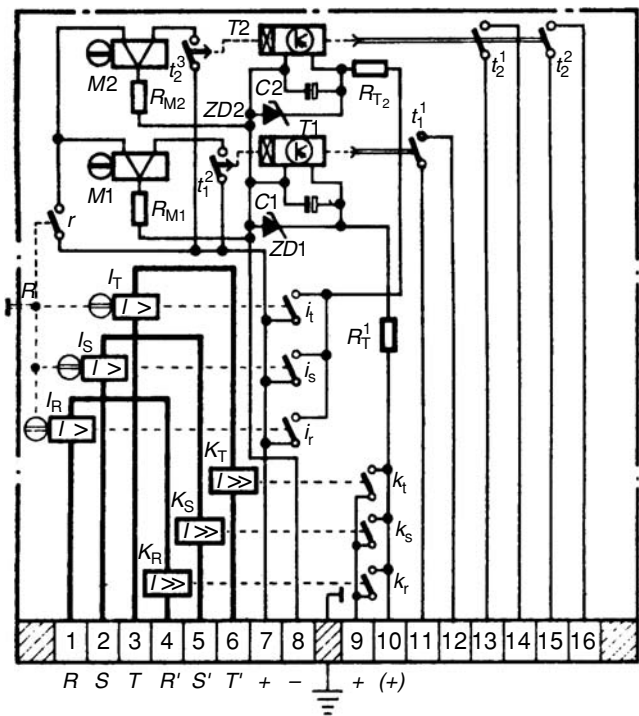


FIGURE 10.68
The RSZ3yk-type current relay, with two TD elements. (AEG 1975).

the previously considered one is an additional indicating relay (M) opening the colored flag at the pickup.

The use of a simple and light TD element enabled installation of two such elements with different TDs in the same case of the current relay (Figure 10.68). One of them (with a longer TD) runs from the current relay $I>$ as in all previously considered cases, and the other (with a shorter TD) runs from the relay $I\gg$, allowing for adjustment of the pick-up time of the relay $I\gg$ within some narrow limits at the stable value of this TD.

This development of current relays, that is the transition from a heavy and expensive mechanical time element to a one based on a semiconductor, seems quite logical. The only astonishing fact is that all of these modifications of relays have been produced by the AEG Company, parallel to each other for many years!

Analyzing the tendencies of development of protective relays from the appearance of transistors and then chips, one notices that not only the AEG Company but also many other companies produced in parallel both mechanical relays designed tens of years ago, and the most modern (for that time) transistor relays, than microelectronic ones, and finally microprocessor ones. How can this phenomenon be explained? The answer to this question is probably evident: constant demand for electromechanical relays. Why should such a demand still remain high, is another question requiring separate treatment and we will return to it later. Logically, if one follows tendencies of technical developments in the 1960–70’s, right after the hybrid relays considered above (containing both mechanical and electronic elements), fully electronic relays without electromechanical sensitive current units should have appeared.

10.4.3 Electronic Current Relays with Independent Time-Delay

We have already considered principles of construction of electronic relay circuits turning from one stable state to another when the input value of the given pick-up threshold is



FIGURE 10.69
Fully electronic current relay, with an integrated TD element of the RSZ 3my type (AEG). Front panel view. To the left above — output electromagnetic relay. $J>$ and $J\gg$ equal $I>$ and $I\gg$, respectively; $t_{J>}$ (s) = scale of TD in seconds; J_e (A) = scale of pick-up currents in amperes (for the unit $I>$); J_k/J_e = ratio of the pick-up current (for the unit $I\gg$).

exceeded. Semiconductor current relays are based on the similar principles. The construction of such relays contains a metal or plastic case with input CTs (as a rule there are three of them) and several printed circuit boards with electronic components. Usually, the auxiliary neutral electromagnetic relay is used as an output element (Figure 10.69).

It should be noted that production of the relay is a high-quality one. The output electromagnetic relay (in Figure 10.69 at the upper left) is used in its sealed modification. Printed circuit boards with discrete elements are covered (by dipping) with a thick layer of high-quality varnish protecting the board from humid air (Figure 10.70). As it can be seen from the circuit shown in Figure 10.71, the three-phase current converted to voltage

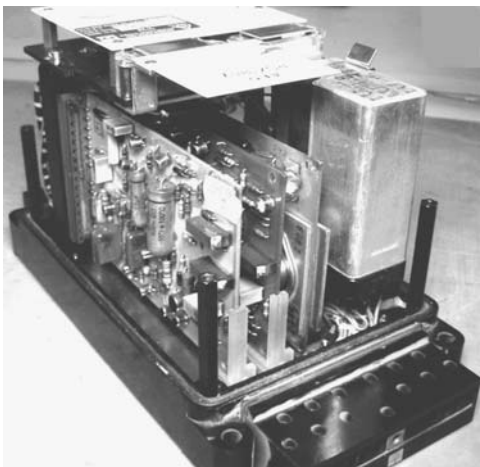


FIGURE 10.70
Electronic current relay of the RSZ 3my-type made on discrete electronic components. View from printed circuit boards.

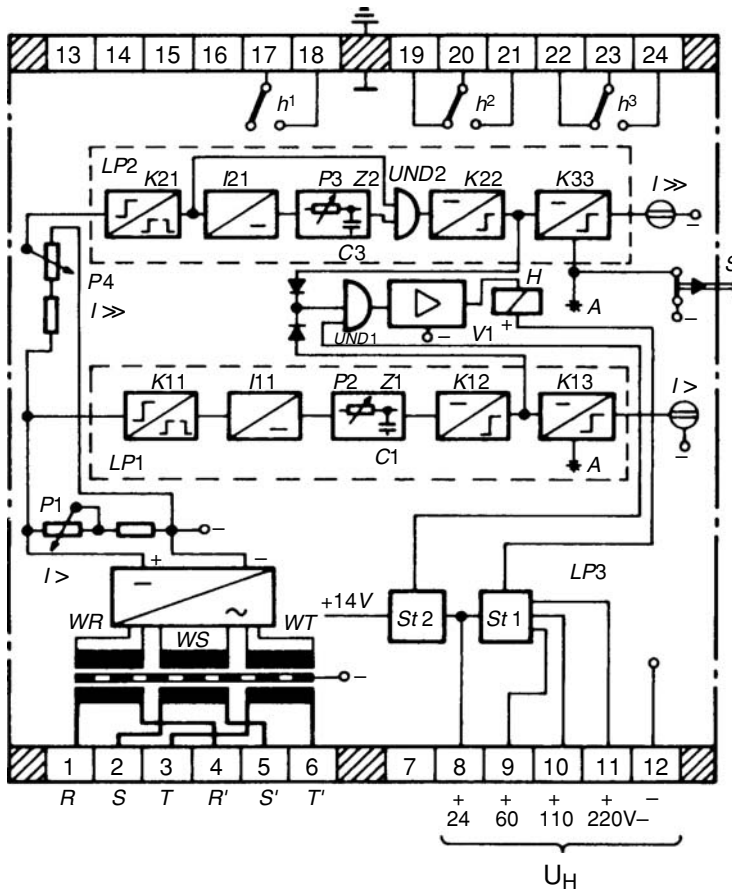


FIGURE 10.71
Circuit diagram of RSZ-3my type current relay (AEG 1975).

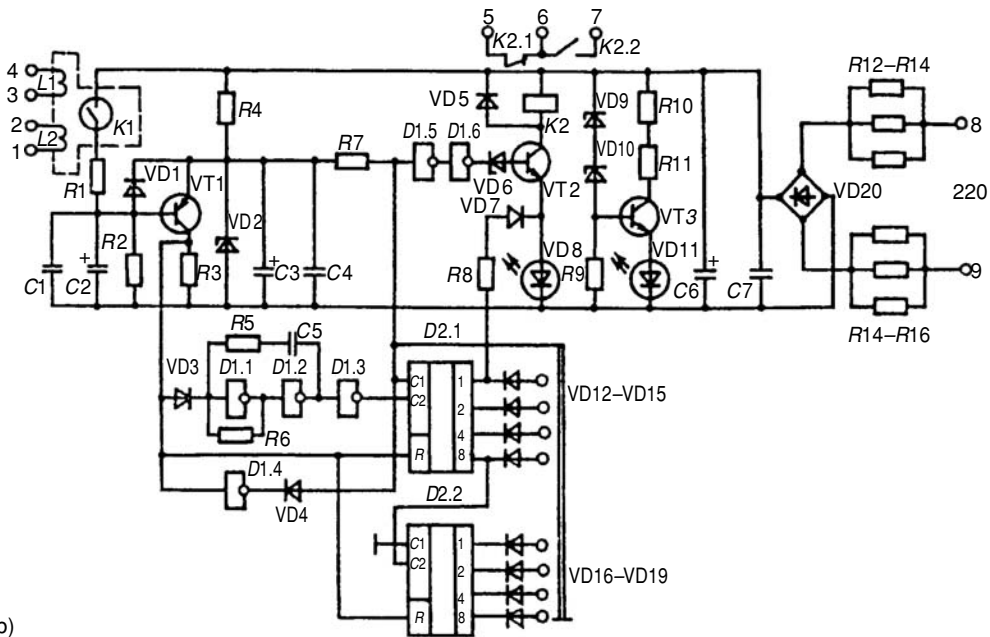
with the help of the input transformers WR, WS, and WT is rectified and applied to two current relays: $I>$ placed on the printed circuit board LP1, and $I\gg$ placed on the second printed circuit board LP2. Pick-up currents of these relays are adjusted by potentiometers P1 and P4, respectively. On the third printed circuit board LP3, there are stabilizers St1 and St2, allowing internal circuit supply from an external source with voltage of 24, 60, 110, and 220 V. The TD is provided by units Z1 (for $I>$) and Z2 (for $I\gg$), working on the principle of RC-circuit charging. Charging time (that is TD) is adjusted by potentiometers P2 and P3 (it is only potentiometer P2 that is brought out to the front panel).

The author had a chance to test such a relay after it had been used in an electric power station. The results were good for a relay which had served for 29 years, without repair, and show that a well-proven circuit, use of high-quality electronic components and properly chosen modes of operation for them allow even relatively simple electronic devices without modern chips or microprocessors, to remain quite competitive, at least from the point of view of stability of parameters and reliability of operation. Moreover, according to the personal experience of the author, modern microprocessor relays do not always provide as reliable protection of electric units as these old relays based on discrete elements.

Because of this and some other reasons quasi-electronic current relays on discrete electronic elements of the "Qusitron" series considered above, still remain promising, and a TD feature can also be added to this promising construction (Figure 10.72). The TD body in this construction is made not on the basis of an RC-circuit as in the



(a)



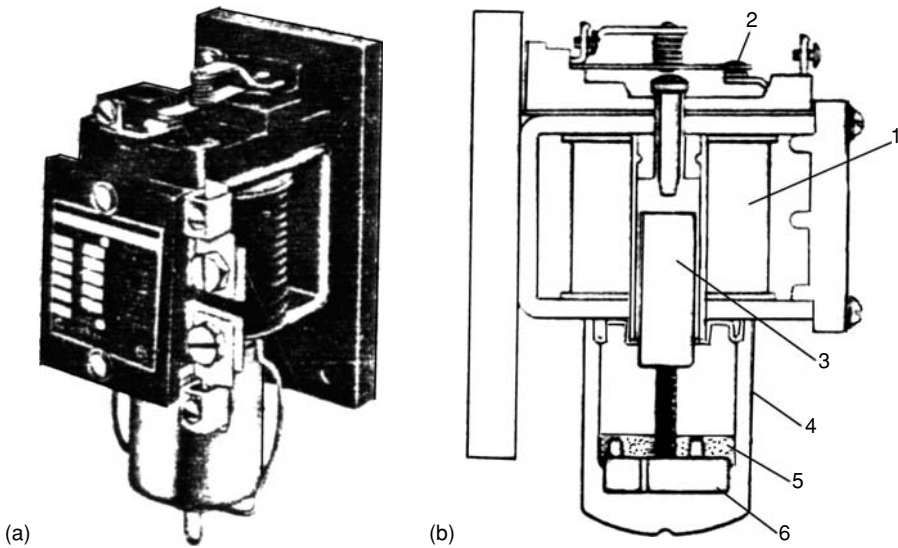
(b)

FIGURE 10.72 Universal hybrid current relay “Quasitron-T” with an integrated TD element, designed by the author. External design (a) and circuit diagram (b).

constructions considered above, but in the form of a pulse generator (multivibrator) on the chip D1 (elements D1.1 and D1.2) and a counter on the chip D2 counting these pulses. The time dial is adjustable, with a range of 0.1 to 25 sec ($\pm 2.0\%$), with a grade of 0.1 sec

10.5 Current Relays with Dependent Time-Delays

The types of secondary relays considered above have an independent on current (fixed) TD, which is not always enough for effective protection from overloading. Much better protection would be provided by a TD that depends inversely on the current value of overloading. At small ratios of overloading the time will be just a few or tens of seconds

**FIGURE 10.73**

Inverse time-current relay "Bulletin 810" type (Allen Bradley, Inverse Time Current Relays Instruction Bulletin 810, 1976). 1 — Operating coil; 2 — contacts; 3 — core; 4 — dashpot; 5 — silicon fluid; 6 — piston.

and at higher ones — fractions of a second. The transition must be smooth: the greater the current, the quicker the relay pick-ups. This is how effective and widely used thermal relays work (see above).

Realization of this problem led to the appearance of relays with inverse dependent time-current characteristics. Nowadays such characteristics are implemented in two types of relays: induction ones (with a disk or a cup rotating in the magnetic field), and electronic ones. However, from the very first years of relay development up to the 1970s and 1980s, there were attempts to create relays with inverse time-current characteristics based on other principles (Figure 10.73).

10.5.1 Relays with a Liquid Time-Delay Element

The Bulletin 810 (produced by the Allen Bradley Company in 1976) has inverse time-current characteristics that are dependent on the viscosity of the fluid in the dashpot; however, unlike thermal relays minimum operating current is independent of ambient temperature change or cumulative heating. Current through the Bulletin 810 operating coil imparts an electromagnetic force on the movable core. The vertical position of the core in the coil is adjustable, thereby providing an adjustable trip point. When the coil current increases to the trip point, the core raises to operate the contact mechanism. TD is provided by a silicone fluid dashpot mounted below the core and coil assembly. An adjustable valve in the dashpot piston provides for TD adjustment. Upward motion of core and piston is dampened through the use of the silicon fluid dashpot. The core rises slowly until the piston reaches an increased diameter in the dashpot, where it is free to trip the contact with quick action. The time and current required to complete this cycle are inversely related as shown by the time-current curves (Figure 10.74).

Standard models of the Bulletin 810 are automatically released as soon as the current through the coil is decreased to approximately 20% of the pick-up current. The core is

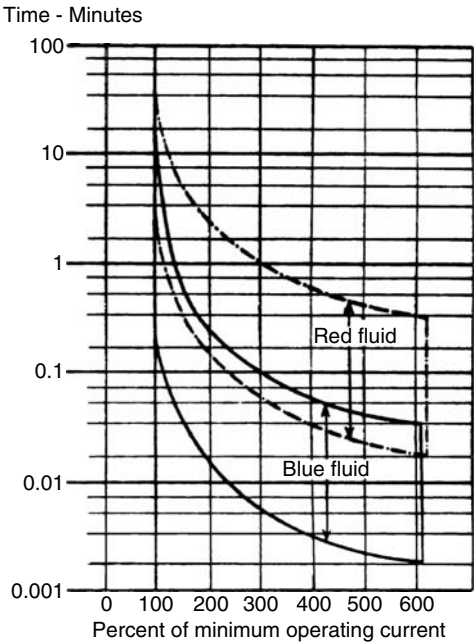


FIGURE 10.74
Inverse time–current curves of Bulletin 810 for silicon fluid with high (red) and low (blue) viscosity.

TABLE 10.1
Time–Temperature Relationship (+40°C Reference)

Ambient temperature (°C)	0	–10	–20	–30	–40
Operating time correction factor	2.25	1.80	1.45	1.20	1.0

designed to drop quickly, returning the contacts to their normal position. A check valve allows the position to bypass the fluid in its return to the bottom of the dashpot so there is no waiting period as with thermal relays.

The minimum operating current (100% on the time–current characteristics graph) is independent of ambient temperatures at the relay; however, the operating time at over-current varies directly according to the viscosity of the silicone fluid. Since the viscosity varies inversely with ambient temperature, the operating time is also inversely affected. The time–temperature table shows the proper correction factors to be applied to the operating times for various temperatures (Table 10.1).

10.5.2 Induction Relays: Design and Characteristics

Induction relays are based on a different principle than the other devices considered above. As it is known, if one places a conducting element in an alternating magnetic field an electric current will be created in this element. This current creates its own magnetic field, biased on 90° from the external field that has created it.

These two magnetic fields can interact with each other and as a result a torque appears that can be used for closing of contacts. In induction relays, a coil serves as a source of an alternating magnetic field and the conducting element is made in the form of a light aluminum disk, a hollow rotor in the form of a cup or a frame that is free to rotate around its axis. In order for the torque to appear, the movable elements must start moving, and for

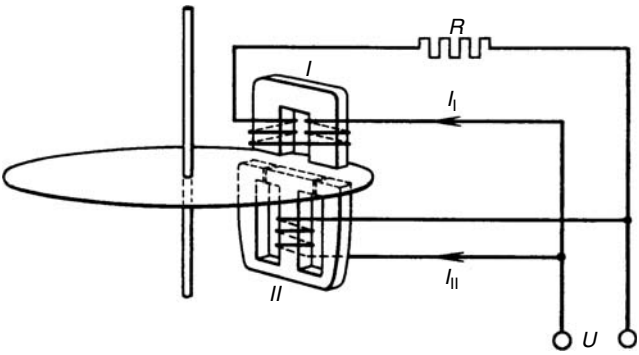


FIGURE 10.75
An induction magnetic system of the tangential type with a rotating disk.

that it must be affected by not less than two alternating magnetic fluxes displaced in space and in time from each other (that is out of phase). These requirements can be implemented in different ways. For example, if one places two coils, one on each side at the edge of the aluminum disk, and switches one of them with a greater number of turns (that is with greater inductance) directly to the source of the input voltage (U) and the other one with a less number of turns in series to the additional active resistance (R) (Figure 10.75), the magnetic fluxes created by the upper and lower coils will be biased in phase.

One can also obtain magnetic fluxes biased in phase by arranging the windings in space in some special way (Figure 10.76). It should be noted that Westinghouse already

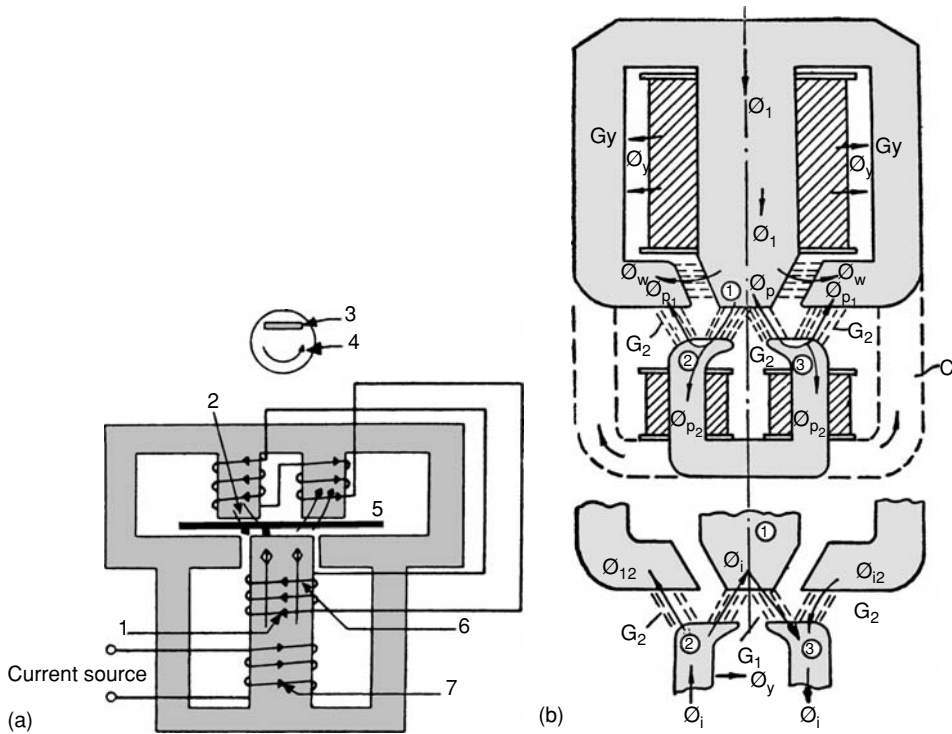


FIGURE 10.76
(a) Construction of the magnetic system of a CO-type induction relay (Westinghouse). 1 — Secondary current; 2 — upper pole flux; 3 — pole electromagnet; 4 — direction of disk rotation; 5 — disk; 6 — main pole flux; 7 — main pole current. (b) Magnetic fluxes in the induction magnetic system of the so-called "tangential" type with a rotating disk.

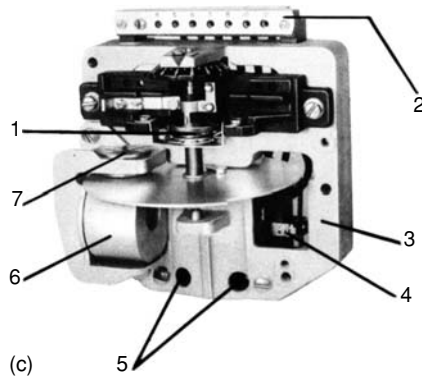


FIGURE 10.76 (Continued)

(c) External design of the magnetic system of a CO type relay (Westinghouse). 1 — Spring tension adjustment; 2 — tap block; 3 — rigid one-piece die-cast frame; 4 — tap value adjustment; 5 — magnet plugs (in electromagnet); 6 — damping magnet; 7 — magnet adjustment.

produced the first induction relays of this type in 1901, and CO-type relays have a history dating back to 1914. Relays of this type have been produced for decades and were a kind of standard on which new projects were based until the 1950s (Figure 10.76b).

This arrangement allows the magnetic fluxes of the coils (Figure 10.76c) to run through the disk edge, causing disk rotation as a result of the interaction with its magnetic field, occurring on the section near the disk edge.

Another example is the so-called shielded magnetic system (Figure 10.77). The shield here is a copper-shading ring put on the shaded pole of the magnetic core. We have already considered this construction in the section devoted to magnetic systems of the electro-

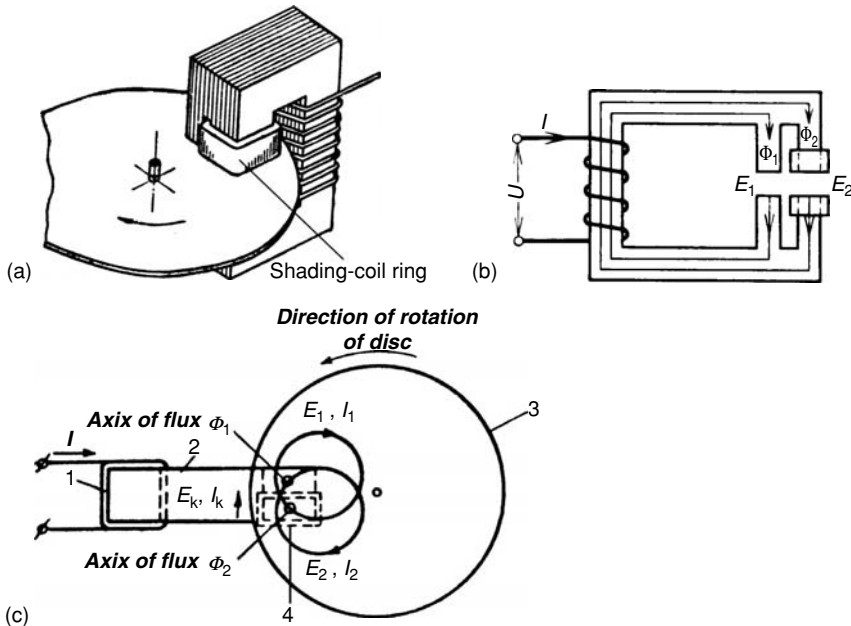


FIGURE 10.77

(a) Induction magnetic system of the shielded type: External view and design. (b) Induction magnetic system of the shielded type: Operating principle. 1 — Coil; 2 — magnetic core; 3 — disk; 4 — shield (shading-coil ring).

magnetic relays. In a standard clapper-type AC relay, this ring prevents the armature from vibrating because the magnetic flux created by this ring is biased by 90° from the main magnetic flux, which is why the total magnetic flux affecting the armature never reaches zero as the main flux changes sinusoidally. The induction magnetic system uses the property of this ring to create additional flux biased by 90° , for torque on the aluminum disk. As the rotating disk crosses the magnetic fluxes (setting it in motion), there a so-called cutting current appears, preventing disk movement according to the Lenz law. It not only prevents movement, but also takes on a stabilizing affect at higher rotation rates of the disk, the greater the cutting current is. To intensify this effect an additional permanent magnet, the poles of which cover the disk edge, is used in some induction relays. The exposure degree of the magnet on the disk depends on its power and position on the disk. In relays with a permanent magnet, there is usually an adjusting mechanism providing radial displacement of this magnet within some limits.

Instead of a disk, a hollow rotor in the form of a cup can be used in induction relays. This rotor has a much smaller diameter and arm of force than the disk, which is why two sources of the magnetic field biased in space and in time are not enough for its rotation, unlike the case with a disk. A magnetic system of at least with four poles is used for rotor rotation (Figure 10.78). Such a magnetic system implies the use of two coils arranged on the core arms in such a way that the pole axes of these coils intersect at the right angle. This means that the magnetic fluxes of these coils are also biased at this angle in space. The phase shift between currents in these coils is determined either by parameters of current (voltage) sources, to which these windings are connected or created artificially with the help of a capacitor (if only one source is used).

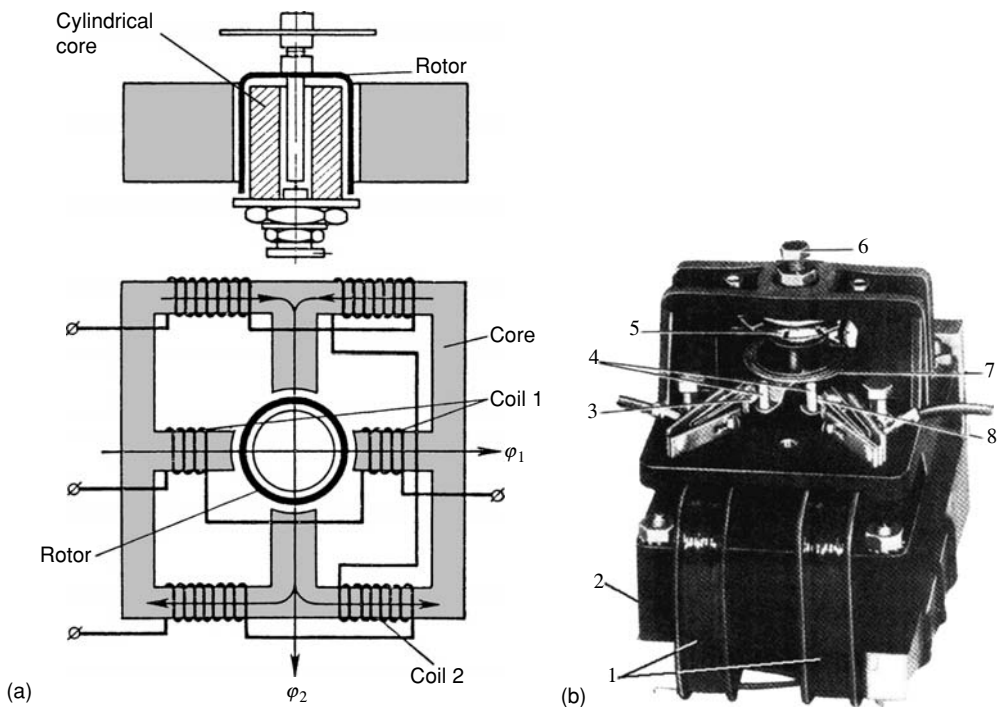


FIGURE 10.78

(a) Construction diagram of the induction magnetic system of a four-pole type with a rotating rotor. (b) External design of the unit of the induction magnetic system of a four-pole type with a rotating rotor. 1 — Coils; 2 — ferromagnetic core; 3 — normally open stationary contact; 4 — moving contacts; 5 — spring adjusting ring; 6 — upper pivot assembly; 7 — upper control spring; 8 — normally closed stationary contact.

As the torque in induction systems is the function of frequency, amplitude of magnetic fluxes, and phase angle between them, these systems can be applied in relays of different purposes:

- Current and voltage relays
- Frequency relays
- Active and reactive power relays
- Impedance relays, etc.

It should be noted that protective relays based on these principles have been in existence for 75 years already. Apparently current relays were the first application of induction magnetic systems. Earlier constructions (Figure 10.79) already contained practically all the elements of modern relays but were not good enough.

For example, early models (Figure 10.79) had quite a primitive reduction gear with a large gear ratio, allowing a great number of disk revolutions until the relay picked up. This construction is made in the form of a thread (2), which is wound around the axis while the disk is rotating and which pulls the movable contact to the stationary one.

Also in the 1940–50's, relays based on an induction system of tangential type were also produced (Figure 10.80). The principle of operation of them has been considered above. In this relay, the thread has already been replaced with a real worm-gearing.

Induction relay RIK type with very complex kinematics to have no parallel, designed by ASEA (Sweden) in 1930's was a model for modern Russian RT-80 series relays (Figure 10.81).

The disk axis in this construction is fixed with the help of bearings (4 and 5) in the frame (5), which can also rotate in bearings 7 and 8. That is, the disk in this construction can move. In the initial position the spring draws off the frame (6) in such a way that the worm (3) does not touch the toothed quadrant (17).

At a certain current value in the winding, due to the factors described above, the disk begins to rotate. When the disk reaches a certain rotation speed, depending on the

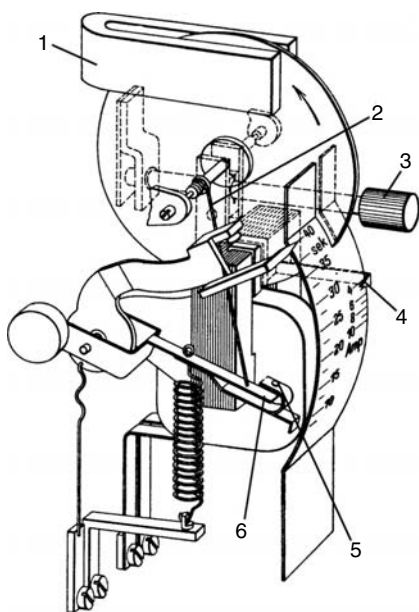
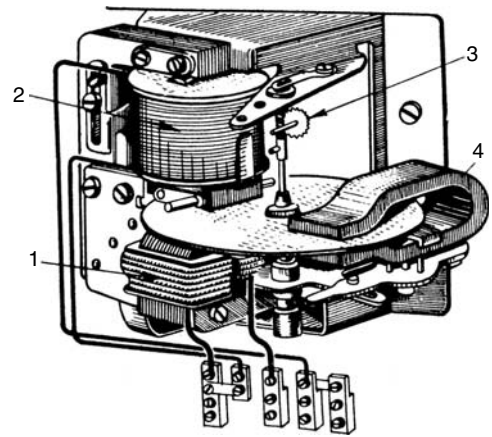
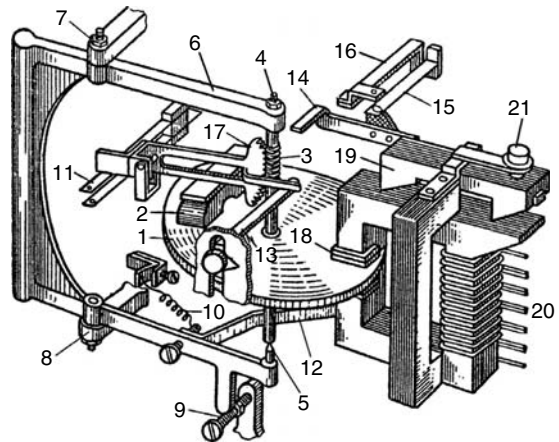


FIGURE 10.79

Induction current relay with a vertical rotating disk, produced by Siemens in the 1930s. 1 — Permanent magnet; 2 — thread; 3 and 4 — setting handles of pickup current and TD; 5 and 6 — contacts of the relay.

**FIGURE 10.80**

A protective relay on the basis of an induction system of the tangential type, produced in the 1940–50's. 1 — First coil; 2 — second coil; 3 — worm-gear; 4 — permanent magnet.

**FIGURE 10.81**

Construction of an induction current relay of the IT-80 (PT-80) series, produced in Russia. 1 — Aluminum disk; 2 — permanent magnet; 3 — worm; 4–8 — bearings; 9 — limiter; 10 — spring; 11 — low-power signal contacts; 12 — ferromagnetic plate; 13 — stop; 14 — lever; 15, 16 — main contacts; 17 — toothed quadrant; 18 — shading-coil ring; 19 — armature rotating around the axis; 20 — coil outlets; 21 — adjusting screw.

current value in the winding, all forces affecting the disk including the magnetic field (2) lead to some resultant mechanical force applied to the disk axis. This force is transmitted to the frame (6), which rotates quite quickly in bearings 7 and 8, together with the rotating disk until the worm (3) touches and hooks the toothed quadrant (17). At that moment the TD of the relay starts counting. When the frame (6) rotates and the ferromagnetic plate (12) approaches the magnetic core, it is picked up by the magnetic field of dispersion and pressed to the magnetic core, thus providing fixation of the position of the frame (6) and reliable operation of the worm-gearing. When the disk rotates further, the toothed quadrant (17) with the pusher raises and closes the main contacts (15 and 16) affecting the lever (14). As the lever (14) is linked not only with the contacts, but also with the left end of the rotating armature (19) this end also goes up, bringing the right end near the special ledge of the magnetic core. At a certain gap the right end of the armature is taken by the magnetic field and safely engages with the magnetic core, providing reliable fixation and good pressure on the main contacts. When the current in the winding increases, the working torque affecting the disk increases proportionally to the current square, and then considerably more slowly because of saturation of the magnetic core (when the magnetic core is saturated, the increase of current in the coil does not lead to an increase of the magnetic flux in the working gap). Accordingly, the pick-up time of the relay is sharply reduced at first when the current goes up (the dependent part of the characteristic: $I >$), and then

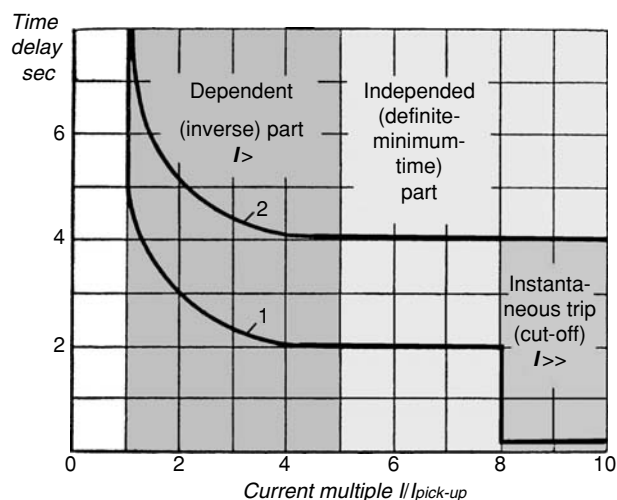


FIGURE 10.82

Time-current characteristics of the PT-80 relay. 1 — For setting $t = 2$ sec and multiple cut-off setting of 8; 2 — for setting $t = 4$ sec (without cut-off unit).

becomes practically constant (the independent part of the characteristic) (Figure 10.82). For relays of this type, the independent part of this characteristic starts approximately at an eight-to-tenfold pick-up current.

At such current ratios the right end of the armature (19) is immediately attracted to the magnetic core, providing closing of the main contacts long before the disk starts to rotate. The pick-up current of this part of the relay ($I \gg$) is adjusted by changing the air gap with the help of the screw (21).

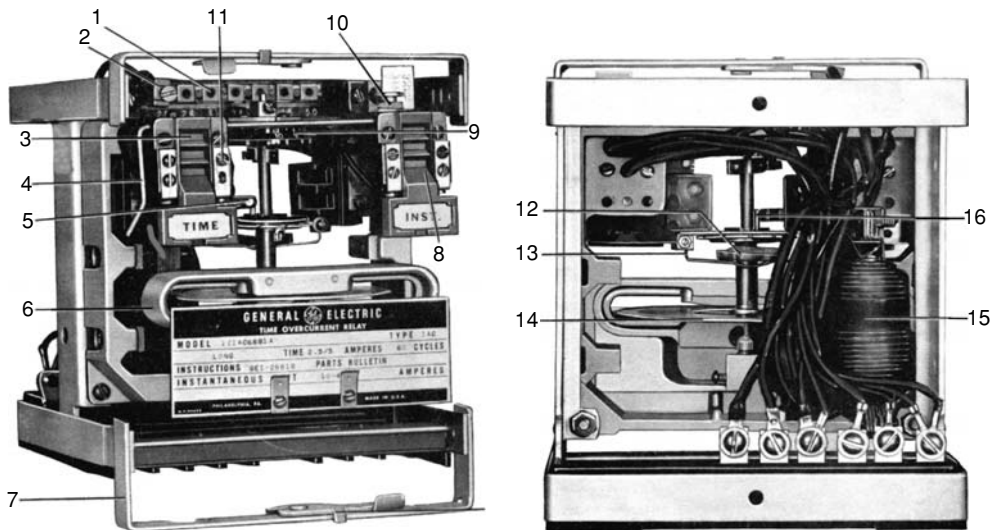
There are 12 modifications of relays of the PT-80 series, for currents ranging from 2 to 10 A, and time settings from 0.5 to 16 sec.

Induction current relays with dependent characteristics, of the IAC and IFC series (a modernized IAC relay with its size reduced by 25%) produced by General Electric Co. for many years, have considerably simpler constructions (Figure 10.83). According to GE statistics, the total working time of these relays, used in various power units all around the world, is 15 million relay-hours.!

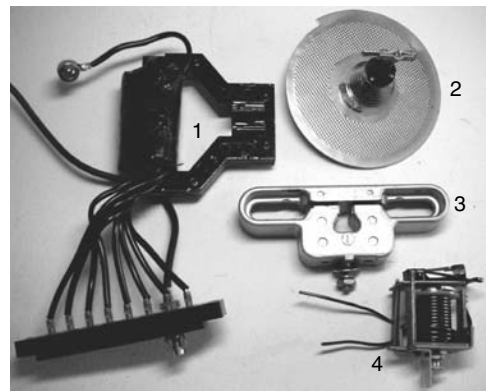
Unlike the previous construction, with complex kinematics in which the disk made many revolutions until the contacts closed, IAC relays are very simple (Figure 10.84) and do not contain any mechanical transmission. The required TDs at low currents are provided due to the very small rotation of the disk. Instantaneous cut-off is provided by a separate relay (8) of the clapper type. The contact, closed by the disk, switches the auxiliary relay (3) with its powerful output contacts, and a drop-out flag signals the pick-up of the relay.

The nominal pick-up current is fixed with the help of a simple switch of coil taps (tap setting). The current at which the disk begins to move (pick-up) is adjusted by changing the tension of the spiral spring. The time dial setting is chosen in accordance with the initial position change of the unit with the spring and the movable contact. The distance that the movable contact must travel before closing, and therefore the operate time of the relay, also changes. One can make an additional adjustment of the operate time by shifting the permanent magnet along the disk radius. A lot of credit goes to the designers of this relay who created a reliable construction, having stable characteristics, that has been used all over the world for decades, with a minimal set of elements.

The protective properties of induction current relays are determined by the form of their time-current characteristics, which may differ (the slope of the characteristic, its curvature) in various relays of different types. The characteristics of protective relays

**FIGURE 10.83**

Induction current relay with dependent characteristic of the IAC series, produced by General Electric Co. 1 — Tap block; 2 — sliding lead; 3 — target seal-in unit; 4 — reset armature; 5 — stationary contact of induction unit; 6 — drag magnet; 7 — cradle; 8 — instantaneous unit; 9 — time dial; 10 — adjustable core; 11 — target seal-in unit coil taps. 12 — control spring; 13 — control spring support; 14 — disc; 15 — coil with U-share magnetic core; 16 — moving contact of induction unit. (General Electric Time Overcurrent Relays).

**FIGURE 10.84**

The basic set of elements of the IAC relay. 1 — Coil with U-share magnetic core; 2 — disc with spiral spring and movable contact; 3 — magnet; 4 — instantaneous unit.

must be well matched with the parameters of the protected object, which is why it is important to distinguish between these characteristics. Western producers apply a special classification that includes six types of characteristics: inverse (or normal inverse); very inverse; extremely inverse; short-time inverse; medium-time inverse; long-time inverse (British Standard 142). The most commonly used and popular are the first three (Figure 10.85 and Figure 10.86).

The *normal inverse* (or inverse) characteristic is most suitable for systems where there is a large variation of fault-current for different fault locations (i.e., the source impedance is much smaller than the line impedances). The inverse characteristic enables improved utilization of the protected object's overload capacity, and increased cold-load pick-up capability compared with the definite-time characteristic.

Very inverse characteristic: The operating time is more dependent on fault-current magnitude; therefore this characteristic is suited for systems where there is a fairly large

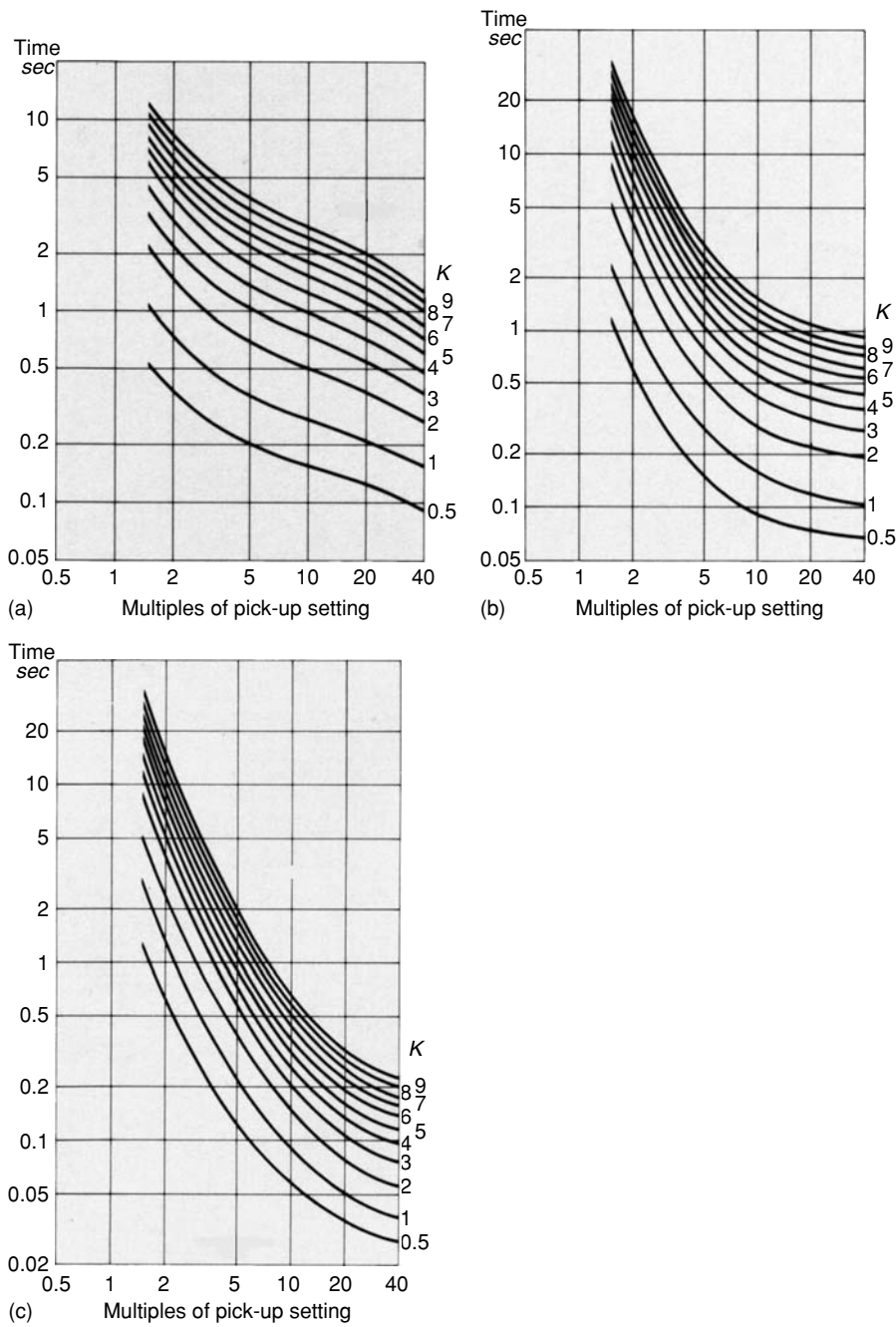


FIGURE 10.85
(a) Time-current characteristics of the “inverse” type (the example used here is an IFC-51 relay, produced by GE). K — time dial setting. (b) Time-current characteristics of the “very inverse” type (this example is an IFC-53 relay, also produced by GE). (c) Time-current characteristics of the “extremely inverse” type (another example of a IFC-53 relay, produced by GE).

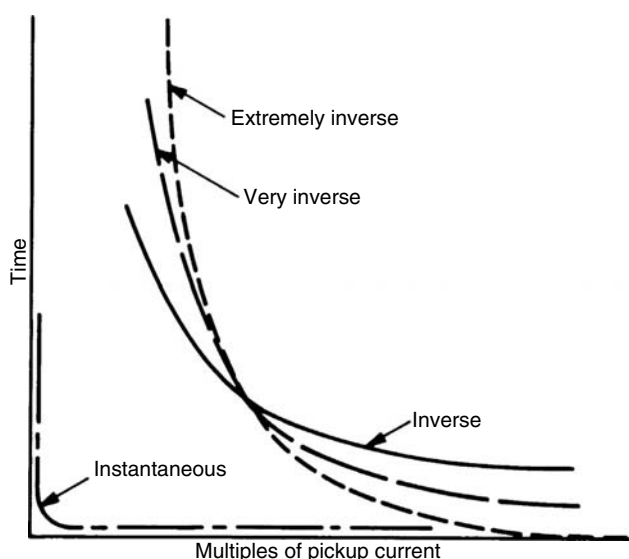


FIGURE 10.86

Characteristic set of most popular types, shown in the same scale for comparison with each other.

variation in fault-current for different fault locations (i.e., the source impedance is less than the line impedances). Where line impedance has a large influence on the fault-current level the very inverse characteristic often permits faster overall fault clearance than do normal inverse characteristics.

The use of inverse-time or very-inverse-time relays for the protection of long lines is generally more satisfactory than for short lines. This is because on a long line there are substantial differences in short-circuit currents, and hence the operating time (depending on whether the fault is near the remote end or the local end of the protected line). This makes it easier to obtain proper time coordination.

Extremely inverse characteristic: The operating time is very dependent on fault-current magnitude. These characteristics are intended for coordinating with fuses on distribution or industrial circuits, and where an extended service outage results in a heavy accumulation of loads of automatically controlled devices (such as water pumps, refrigerators, water heaters, oil burners, etc.). Such load accumulations often produce inrush currents considerably in excess of the full-load feeder current for a short time after the feeder is re-energized. The extremely inverse time relay characteristic permits successful pick-up of these loads and at the same time provides adequate fault protection which can be made selective with fuses and cut-outs in other parts of the circuit.

They are used in situations requiring a high degree of overload capacity utilization, and where cold-load pickup or energizing transient currents could be a problem. They are also suitable for providing coordination in networks where current changes for different fault locations are small but finite and distinguishable.

It is interesting to compare the efficiency of a protection relay having such characteristics, to that of a relay having definite-time (independent) characteristics (see above). Let us remind ourselves that a relay with a definite-time characteristic will have an operating time is independent of the fault-current magnitude. This characteristic is mainly suitable for use in systems where the fault-current magnitude is relatively constant for different fault locations (i.e., source impedance is much larger than line impedances). It also simplifies selectivity planning in conjunction with other relays having instantaneous or definite-time characteristics (Figure 10.87). TD selection should be begun at the farther-

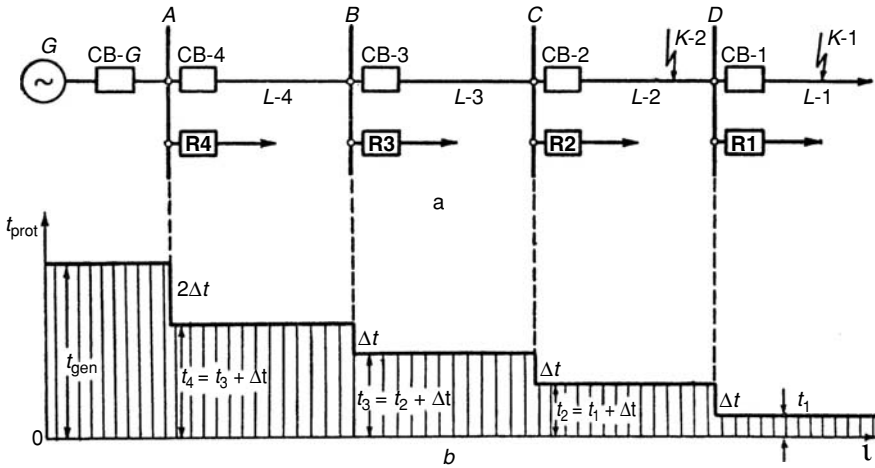


FIGURE 10.87 Radial power transmission line with usage protective relays with an independent TD (a “time-graded” or “stepped” TD).

most circuit section and finally completed at the power source (Figure 10.87). Let us select the minimum possible TD t_1 for the far-end circuit section $L-1$. By reason of selectivity considerations, in order that a fault at point $K-1$ will not lead to disconnection of circuit section $L-2$, the TD for circuit section $L-2$ must be somewhat greater:

$$t_2 = t_1 + \Delta t$$

where Δt = time-delay step or increment necessary as a reliable margin against operation of protection on the succeeding circuit section.

On circuit section $L-3$ the overcurrent protection should operate in a similar fashion with the TD:

$$t_3 = t_2 + \Delta t,$$

etc.

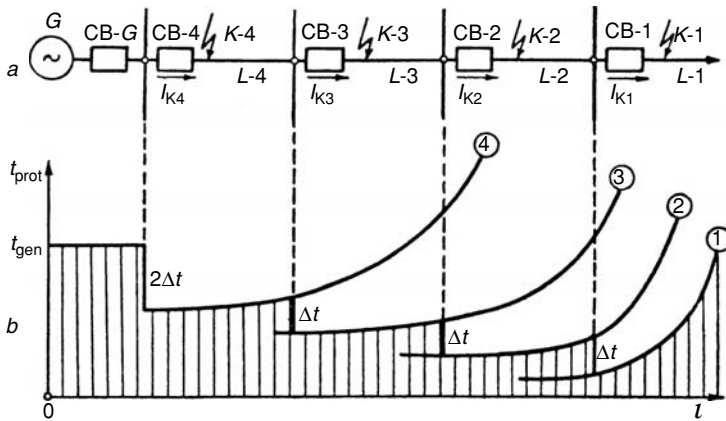
Figure 10.87 shows a diagram with the TDs selected for a system of power circuits and a generator. We can point out here that in order to increase the reliability, the generator protection has a TD setting which includes a double time-delay step, that is

$$t_G = t_4 + 2\Delta t$$

generally $\Delta t = 0.4$ to 0.5 sec.

The major advantage afforded by use of overcurrent relays having inverse-time characteristics is that their TDs are approximately inversely proportional to the short-circuit current or overload current. This property provides the possibility of obtaining simple and quick-acting protections for individual radial circuits against short circuits.

Figure 10.88 shows a system of protection time-delay characteristics in the form of a function $t = f(I)$. They clearly show with what TD the faults are cleared at the various circuit points, not only by the individual protection of a given circuit section (main protection) but also by the protection of the next power-supply-side circuit section (back-up protection). This is another advantage of these relays.

**FIGURE 10.88**

A radial power transmission line with usage protective relays with a dependent TD (an inverse-TD).

Any comparison of Figure 10.87 and Figure 10.88 makes it evident that the nature of the TDs is identical in both cases. In protections using relays with inverse-time characteristics, a fault at the far end of the circuit section is cleared with a greater TD than a fault at the near end (refer to Figure 10.88). To provide an allowance for the greater inertia error of induction-type relays, the time-delay step Δt is equal to 0.7 to 0.8 sec.

As a whole, the application of inverse-time relays results in higher TD levels. This is a disadvantage of these relays. As can be seen, the relay with an extremely inverse characteristic (1) has a smaller effective area than the relay with a normal inverse characteristic (4).

Induction systems with a rotating disk have a certain inertia (because of the large diameter of the disk) which plays no role when these systems are used for relays with a dependent TD; however, these systems cannot be applied in relays with a small TD because the minimum pick-up time of the system with a disk exceeds 0.1 sec.

A modern induction magnetic system (Figure 10.89) of the four-pole type with a rotating rotor of small diameter (as the so-called "Ferraris motor") provides a minimum pick-up time of 0.02 to 0.04 sec and is used for current relays with small TDs.

In May–June 1885 Galileo Ferraris (Figure 10.90a) conceived the idea that two out-of-phase, but synchronized, currents might be used to produce two magnetic fields that could be combined to produce a rotating field without any need for switching or for moving parts. This idea, which is common place to electrical engineers now, was a complete novelty in the 1880s. Ferraris published it in a paper to the Royal Academy of Sciences in Turin in 1888.

Ferraris devised motor (Figure 10.90b) using coils (as electromagnets) at right angles and powered by alternating currents that were 90° out of phase, thus producing a revolving magnetic field. The motor, the direction of which could be reversed by reversing its polarity, proved the solution to the last remaining problem in alternating-current motors. The principle made possible the development of the asynchronous, self-starting electric motor that is still used today.

At the time Ferraris seems not to have thought that his principle would lead to a motor for industrial purposes, but he suggested that it could be used as the basis of a meter for alternating current measurements. Ferraris did not want to take out a patent on his inventions and refused a large sum from an American company, because he thought that the discovery can be put in the service by everyone: "I am a professor, not

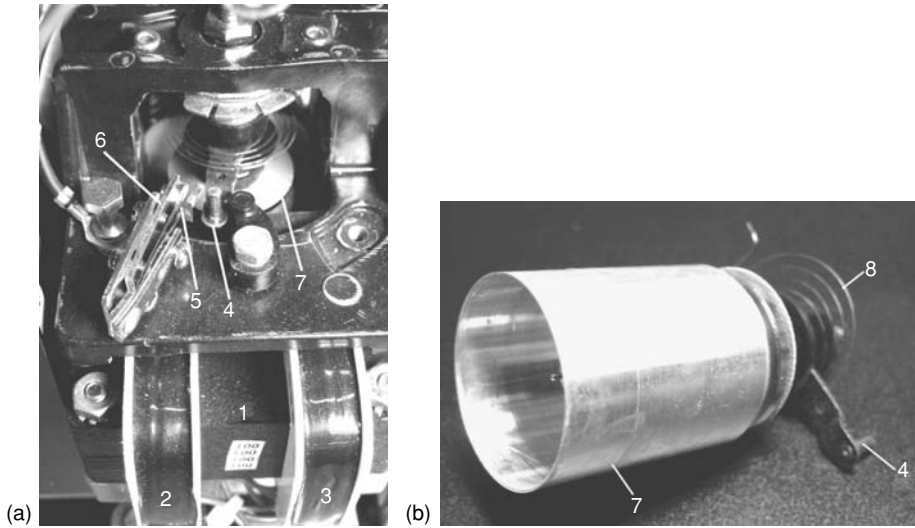


FIGURE 10.89 Rotor and a ready-assembled four-pole induction system. 1 — Magnetic core; 2 and 3 — coils; 4 — pusher of the movable contact; 5 — movable contact; 6 — stationary contact; 7 — rotor; 8 — spring.

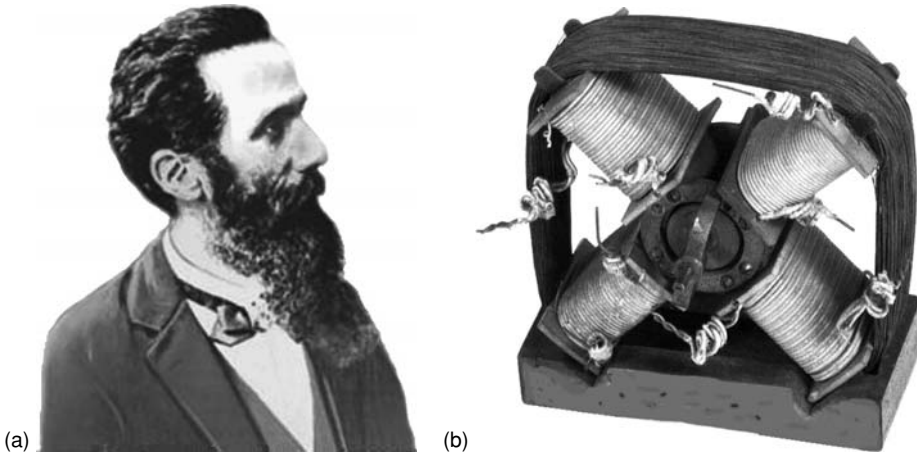
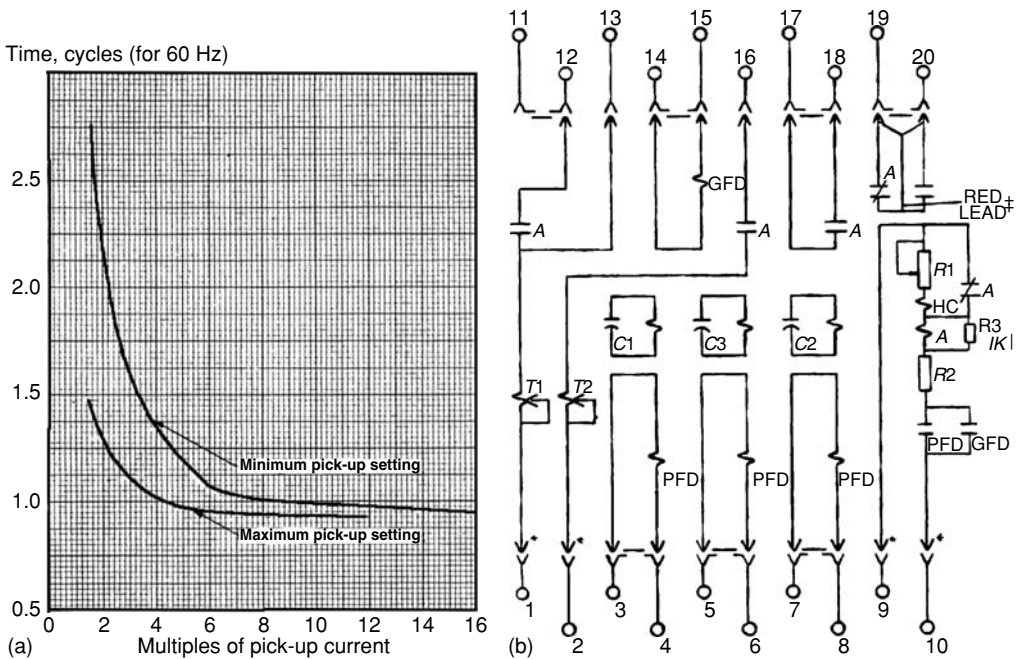


FIGURE 10.90 (a) Galileo Ferraris (1847 to 1897), Italian physicist who studied optics, acoustics, and several fields of electrical engineering. (b) Ferraris motor. Revolving rotor can be seen in central part of construction.

an industrialist,” he said with regard to the offer (now, there are several International Patent Classification indices for devices with Ferraris motor principles: H01H53/12, G01R11/36, G01R5/20).

A typical case of application of such a magnetic system with a rotor is a relay of the CHC11A type, produced by General Electric. When using the CHC11A relay in circuit-breaker-failure back-up schemes, the relay may be called on to carry maximum fault current for some fraction of a second before the fault is cleared. For this reason, the short-time current capability of the relay should be noted. This is particularly true of the hinged-armature unit (without an inverse TD). CHC11A relays have inverse time characteristics for very short TDs (Figure 10.91a).

**FIGURE 10.91**

(a) Time-current characteristics of the CHC11A-type relay. The time is expressed in cycles of AC with a frequency of 60 Hz. Duration of one cycle is $t = 1/60$ sec. (b) Circuit diagram of the CHC11A-type relay in a three-phase modification (General Electric). PFD — Phase-fault detector (induction cup unit); GFD — ground-phase detector (hinged-armature).

The short-time rating of the cup unit is so high that it will probably never be a limiting factor. While the 2 to 8 A cup unit is continuously rated for 5 A, it is capable of carrying 8 A continuously. This is important in multi-breaker bus arrangements, where bus current that the relay may be connected to receive can exceed 5 A during maximum load conditions.

The phase bias required for torque in the four-pole induction magnetic system of the CHC11A-type relay is created with the help of capacitors (C_1 , C_2 , and C_3 in Figure 10.91b).

The induction cup unit is intended for multiphase faults and the small hinged-armature for ground faults.

10.5.3 Electronic Current Relays with Dependent Characteristics

TDs dependent on current are implemented in such relays with the help of the RC-circuit considered above. The charging rate of the capacitor *with constant power supply voltage* is known to be determined by the so-called time constant $\tau = RC$. If one switches a threshold element picking up at a certain voltage level parallel to the capacitor, one can change the TD value by changing the resistance of the resistor R and the value of the capacitor C until this threshold element picks up. This principle is basic for the operation of the time elements with independent characteristics in current relays. Mind the words above in italics “with constant power supply voltage.” This is the requirement for a fixed TD determined only by the parameters R and C . The voltage on the capacitor U_C (that is on the threshed element) increases according to the exponential law (Figure 10.92):

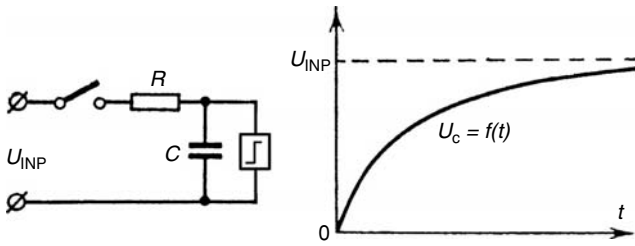


FIGURE 10.92
Basic principle of construction of the TD unit on the basis of an RC-circuit.

$$U_C = U_{INP} \left(1 - e^{-\frac{t}{\tau}}\right),$$

where U_{INP} is the input voltage applied to the RC-circuit; t is the charging time of the capacitor to the voltage U_C .

The threshold element picks up when the voltage on the capacitor U_C reaches the pick-up voltage of the threshold element U_P , and the TD (t_P) to the pick-up equals:

$$t_P = RC \ln \frac{U_{INP}}{U_{INP} - U_P}$$

As can be seen from the latter formula, the TD depends not only on the time constant value (that is on parameters R and C), but also on the input voltage value U_{INP} , which is why special means of stabilization of the input voltage are applied in relays with an independent TD.

On the contrary relays with a dependent TD make use of this property of the RC-circuit. In the latter case, current is converted to voltage (for example, with the help of the input transformer) and is applied to the RC-circuit with the threshold element. The greater the input current (that is the voltage applied to the capacitor) is, the quicker it is charged and the smaller the TD will be until the pickup of the threshold element. This is what is needed for protective current relays with a dependent TD (Figure 10.93). In the initial mode, when current is lesser than a certain threshold value, the contact (S.R.) of the start relay short-circuits the winding (w_2) of the transformer (T_3) through the current-limiting resistor (R_4). As a result, there is no voltage, neither on the charging RC-circuit nor on the winding (w_3) of this transformer. The start relay picks up at the certain value of the input current and de-shunts (by its contact S.R.) the rectifier (VD2), through which the capacitor (C_2) is charging. As the capacitor is charging, the current used by it from the winding (w_2) decreases and the voltage on the winding (w_3), which is rectified, filtered and applied to

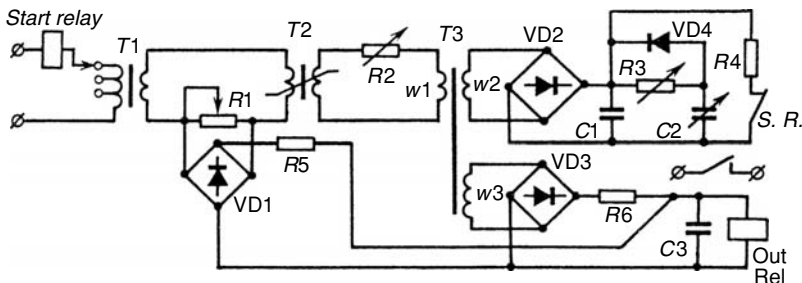


FIGURE 10.93
Circuit diagram of a simple electronic current relay with a dependent TD, based on an RC-circuit.

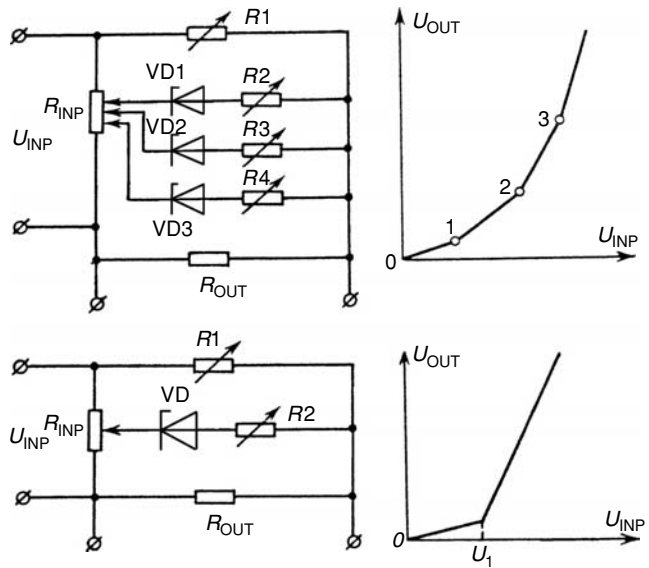


FIGURE 10.94

Principle of forming a specific characteristic with the help of Zener diodes (VD) and resistors: above — with several stages; below — with one stage.

the winding of the output relay, increases. At a certain voltage level this relay picks up. If the input current is great, the voltage drop on the resistor (R_1) becomes great enough for pick up of the output relay before the capacitor (C_2) is charged. This forms the independent part of the characteristic. The dependent part of it is formed when the voltage applied to the capacitor (C_2) is proportional to the input current. At very high current values the transformer (T_2) is saturated and the voltage in the RC-circuit does not increase further, while the current goes up. This allows stabilization of the dependent part of the characteristic.

If one cut in an additional converter of the input voltage on Zener diodes, for instance, with different voltages at the input of those devices (Figure 10.94), it is possible to make the voltage applied to the capacitor charge change, depending on the input current (voltage) according to a specific law. If the input voltage is less than the drop-out voltage of the Zener diodes it is applied to the charging RC-circuit through the resistor (R_1), which corresponds to the first section on the curve. If the input voltage (current) increases and reaches the drop-out voltage of the Zener diodes (VD_1), resistor R_2 appears to be switched parallel to resistor R_1 . At that point the resultant resistance decreases and the curve passes to the second section, and so on. As a result of this process it is possible to obtain different forms of time-current characteristics of the relay. This principle has been in use for quite a long time already, since the 1960s and 1970s (Figure 10.95).

The relay's input has a built-in CT with several secondary windings with taps. Over the switch for the setting of the operating current, the voltage is taken out across a resistor. When this voltage, rectified, smoothed, and compared with above-mentioned voltage, exceeds the reference voltage, the starting relay picks up. At the same time, the RC circuit starts charging up. For the inverse time lag relay the required time characteristic is obtained through a combination of Zener diodes and resistors used in the mentioned RC circuit. When the capacitor in the RC circuit is charged up to a certain voltage level, the tripping relay also picks up. In the three-phase design, the measuring circuit acquires a voltage that is proportional to the largest of the three currents.

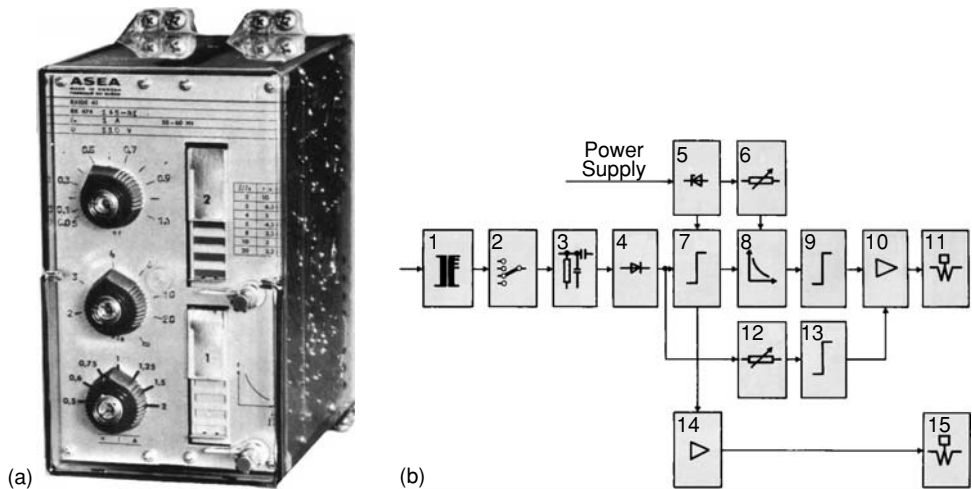


FIGURE 10.95 An electronic relay of the RXIDE-4 type, with a dependent time–current characteristic. External view and block-diagram. 1 — Input transformer; 2 — current setting; 3 — RC-filter; 4 — rectifier; 5 — stabilizing circuit; 6 — time setting; 7 — level detector; 8 — time circuit; 9 — level detector; 10 — amplifier; 11 — tripping relay; 12 — instantaneous setting; 13 — level detector; 14 — amplifier; 15 — starting relay. (ABB Buyer’s Guide 1990.)

Instantaneous operation is obtained by means of the rectified part of the voltage from the transformer being compared to the reference voltage — when the latter is exceeded an operating impulse is given to the tripping relay.

In later constructions of relays, the required time–current characteristics are formed with the help of a specialized microprocessor synthesizer. The time–current characteristics of such relays match exactly the characteristics of induction relays. This relay of the IC91 type, produced by ABB, can serve as a good example of such a relay (Figure 10.96).

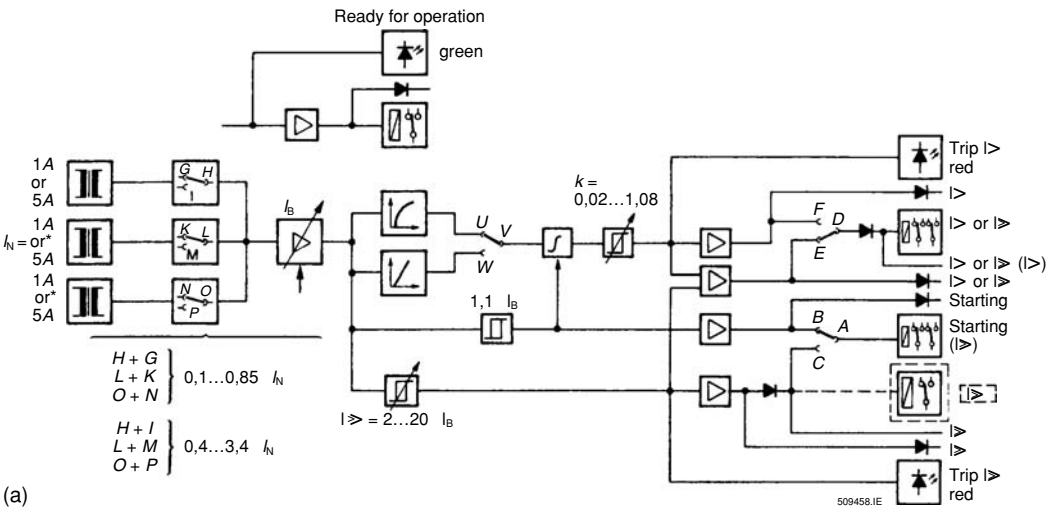


FIGURE 10.96 (a) Block-diagram of a microprocessor current relay of the IC91 type with a dependent characteristic.

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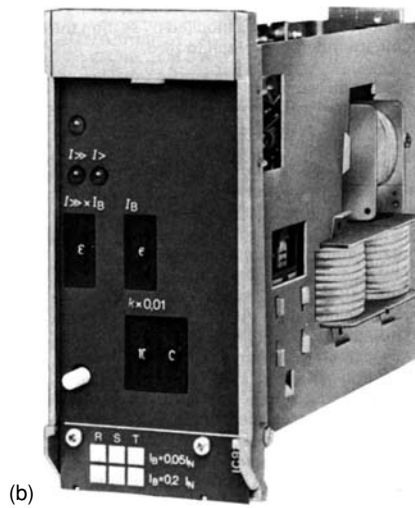


FIGURE 10.96 (Continued)

(b) External design of a microprocessor current relay of the IC91 type, with a dependent characteristic (ABB Buyer's Guide 1990)).

10.6 Harmonic and Voltage Restraint Relays

When a power transformer is energized, current is supplied to the primary, which establishes the required flux in the core. This current is called a “magnetizing inrush” and it flows only through CTs in the primary winding. This causes an unbalanced current to flow in the coil of the current relay, which would cause faulty operation if means were not provided to prevent it.

Power system fault currents are of a nearly pure sine waveform, plus a transient DC-component. The sine waveform results from sinusoidal voltage generation and nearly constant circuit impedance. The DC-component depends on the time in the voltage cycle at which the fault occurs, and upon the circuit impedance magnitude and angle.

Transformer magnetizing inrush currents vary according to the extremely variable exciting impedance resulting from core saturation. In modern transformers, larger than approximately 10 MVA and with orientated sheet-metal, the amplitude of the inrush current can be five to ten times of the rated current when it is connected to the high voltage side, and 10 to 20 times the rated current when it is connected to the low voltage side. The amplitude and duration of the inrush current (up to some few seconds) is dependent on the design of the transformer, its connection, and its neutral earth point, as well as the short-circuiting effects of the network.

These currents have a very distorted waveform made up of sharply peaked half-cycle loops of current on one side of the zero axis, and practically no current during the opposite half cycles. These two current waves are illustrated in [Figure 10.97](#). Any current of distorted, nonsinusoidal waveform may be considered as being composed of a direct-current component plus a number of sine-wave components of different frequencies: one belonging to the fundamental system frequency, and the others, called “harmonics,” having frequencies which are 2, 3, 4, 5, etc., times of the fundamental frequency. The relative magnitudes and phase positions of the harmonics, with reference to the fundamental, determine the waveform. When analyzed in this manner the typical fault

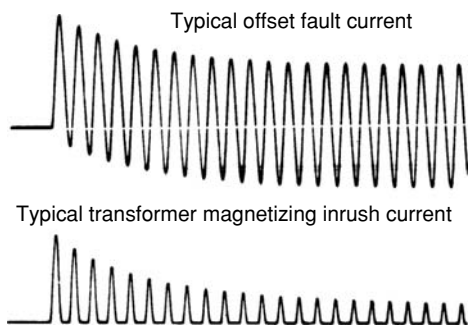


FIGURE 10.97
Typical fault and transformer magnetizing inrush currents.

current wave is found to contain only a very small percentage of harmonics, while the typical magnetizing inrush current wave contains a considerable amount (Table 10.2).

The high percentage of harmonic currents in the magnetizing inrush current wave affords an excellent means of distinguishing it electrically from the fault current wave. In special current relays the harmonic components are separated from the fundamental component by suitable electric filters.

The simplest type of relay with a harmonic restraint characteristic is the PT-40/F-type relay, differing from the PT-40-type relay considered above by a filter formed by inductance of the transformer (*T*) and the value of the capacitor (*C*) (Figure 10.98).

Currents of the highest harmonics are closed through the capacitor (*C*) and not applied to the winding of the relay. The parameters of the elements are chosen in such a way that the pick-up current of the relay at a frequency of 150 Hz is no less greater than eight times that of the pick-up current of the relay at a frequency of 50 Hz. In this way different sensitivities of relays to short-circuit currents (50 Hz) and current rushes of magnetization of the transformer (over 100 Hz) are provided.

Another widespread principle of construction of relays with harmonic restraint is to use a quickly saturated transformer (QST) cut in between the standard current relay and the current source (Figure 10.99). Such a QST is usually made on a triple core (Figure 10.99b), and contains two short-circuited windings (*w3* and *w4*) in addition to the working winding (*w1*) and the secondary winding (*w2*).

In the normal mode of operation, when the current I_1 is sinusoidal, the magnetic flux in the left rod of the transformer equals the sum of magnetic fluxes F_1 and F_2 created by the primary winding *w1* and the short-circuited winding *w4*. At the nominal current value I_1 these fluxes create current I_2 in the secondary winding (*w2*), enough for pick-up of the

TABLE 10.2
Harmonic Analysis of a Typical Transformer Magnetizing Inrush Current Wave

Wave Component	Ratio of Amplitude of Harmonic Component to Amplitude of Fundamental (%)
Fundamental	100
Direct current	57.7
Second harmonic	63.0
Third harmonic	26.8
Fourth harmonic	5.1
Fifth harmonic	4.1
Sixth harmonic	3.7
Seventh harmonic	2.4

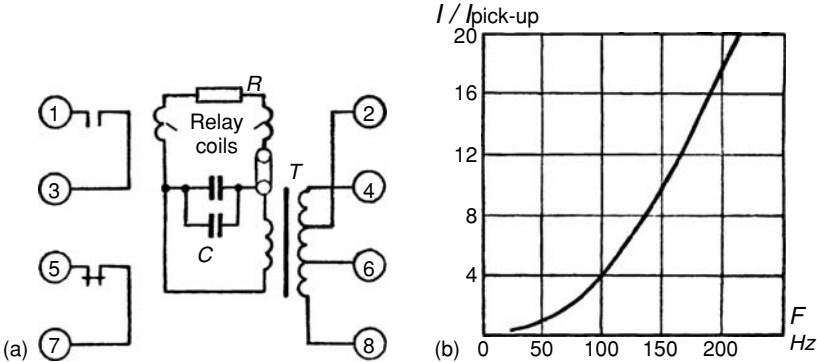


FIGURE 10.98
Circuit and frequency characteristic of the simplest PT-40/F-type relay with a harmonic restraint characteristic.

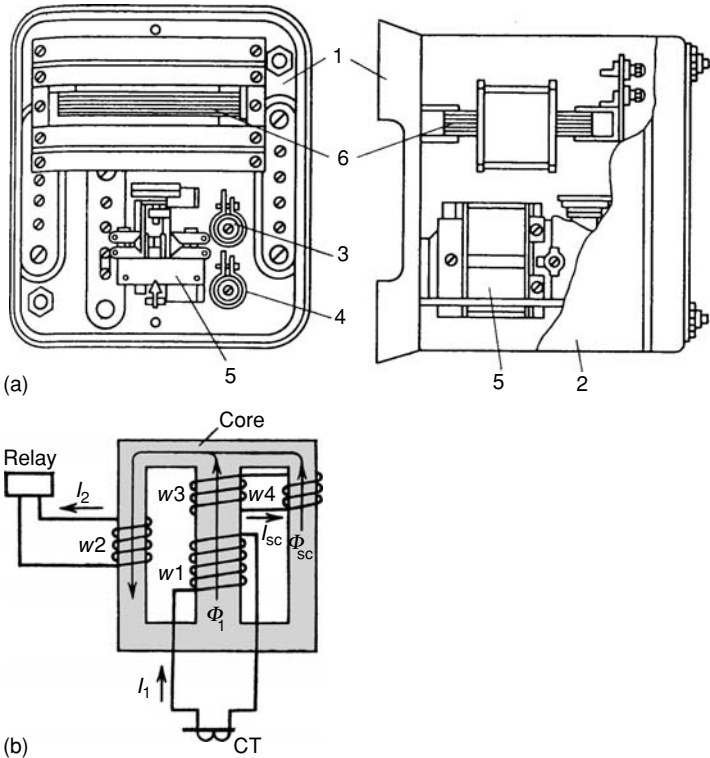


FIGURE 10.99
(a) Current relay of the PHT-565 type (Russia) with harmonic restraint characteristic produced on the basis of a QST. 1 — Heel piece; 2 — case; 3 and 4 — adjusting resistances; 5 — integrated. PT-40 relay (see above); 6 — QST. (b) A simplified circuit of an RNT-565 current relay with a QST.

relay. When the nonsinusoidal magnetizing inrush current starts flowing in the primary winding of the QST, its core is quickly saturated, since this current is unidirectional. As a result, the current transformation to the secondary winding $w2$ is especially reduced due to a decrease of the constituent of this current, obtained from the short-circuited winding. The current I_2 remains very small (not enough for a pick-up of the relay) even at a high amplitude of the input nonsinusoidal current. The principle of offset from rushes of

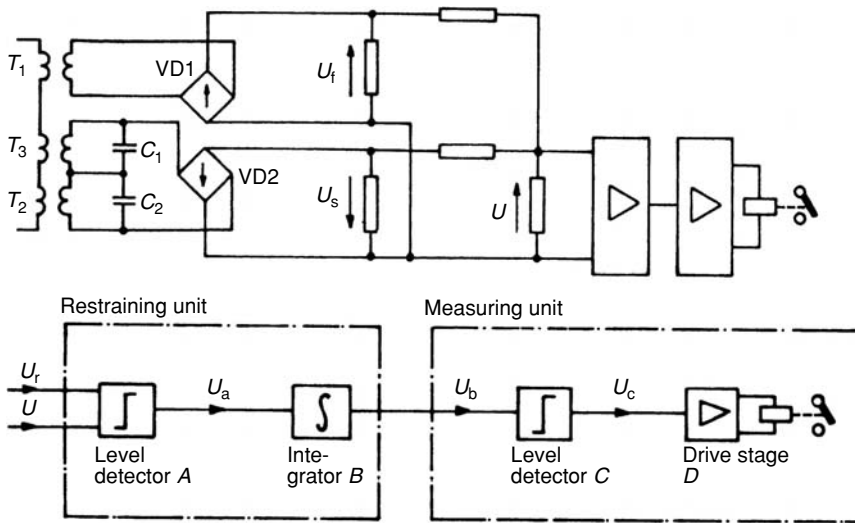


FIGURE 10.100
Block-diagram of harmonic restraint electronic overcurrent relay RAISA type (ABB).

magnetization current with the help of a filter is also used in electronic current relays (Figure 10.100).

The restraining method used in the RAISA relay is based upon the fact that the second harmonic (100 Hz) is relatively much larger in the switching surge than in the short-circuit current. The restraining voltage U_s is obtained via transformers T_3 and T_2 . The inductance of the transformers and the capacitance of the capacitors C_1 and C_2 are tuned for resonance at the second (100 Hz) and the fifth (250 Hz) harmonic components. The second harmonic component is used to restrain the relay from the magnetizing inrush current. The fifth harmonic component is incorporated to attain the desired insensitivity for higher harmonics. The transformers supply the rectifier bridge VD2, which provides the counter-acting voltage U_s for restraining. Voltages U_f and U_s are summated in accordance with their signs to a resultant voltage U , which is supplied to the measuring circuit.

Voltage restraint overcurrent relays are relays, the current pick-up of which changes because of voltage level, not harmonics as the in cases considered above. It is constructed as a standard current relay of the induction type with a rotating disk, but it is also equipped with an additional voltage coil which creates voltage restraint (Figure 10.101 and Figure 10.102). Why are such relays needed?

The voltage restraint overcurrent relay was designed for the purpose of providing external-fault back-up protection for the generator. System fault back-up protection should be provided at the source of faulty currents, the generator. Such protection should protect against the generator continuing to supply short-circuit current to faults in the adjacent system element, because the fault may not have been removed by other protective equipment. The current source for the voltage restraint relay should be a CT at the neutral end of the generator windings, or at the line-side CT. Phase-to-phase voltage should be obtained from the generator potential transformers. Loss of potential to the voltage restraint relay will cause the relay to trip if the generator load current, expressed in relay secondary amperes, is greater than the zero voltage pick-up current of the relay.

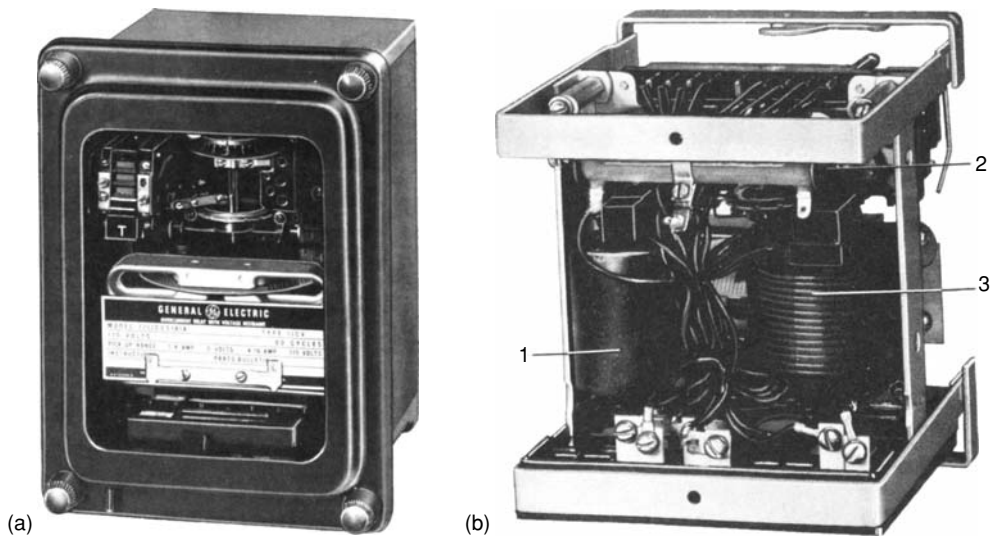


FIGURE 10.101
Time-overcurrent relay with a voltage restraint of the IJCV51 type (GE). 1 — Potential restraint coil; 2 — potential restraint resistor; 3 — current coil. (General Electric Type IJCV Relays with Voltage Restraint).

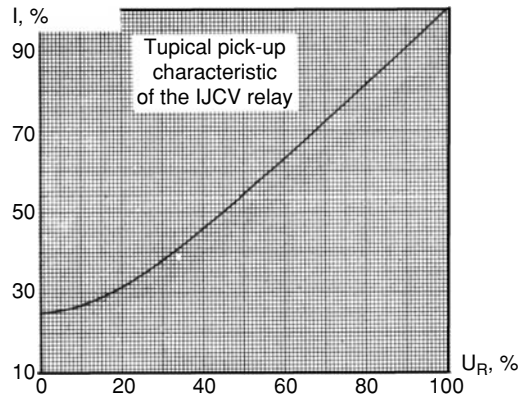


FIGURE 10.102
Typical pick-up characteristic of the type IJCV relay. U_R — percent of rated voltage across restraint circuit; I — current in percent of tap value.

10.7 Pulse Current Relays

The so-called pulse current relay is energized by very short current pulses with duration of just a few microseconds of input. Such relays must have a very small TD, sufficient to pick-ups when partial breakdown of isolation in high-voltage vacuum tube is occurred, or to operations with arresters, when current carry in lightning rods (when lightning strikes), etc., and also must have a long output signal, compatible with ordinary electro-mechanical devices

In micro-electronic devices, especially high-frequency ones, electric signals of small duration are frequently used; therefore electronic circuits for pulse stretch are very widely used in these devices. An example of such a circuit is the RC-integrator ([Figure 10.103](#)).

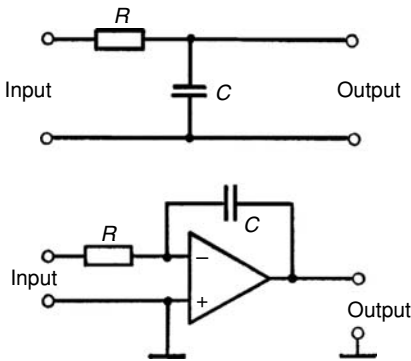


FIGURE 10.103
Examples of simplest RC-integrators, widely used in electronic devices.

For the same purpose the so-called “monostable multivibrator” (or “waiting multivibrator,” “one-shot multivibrator” or “univibrator”) is frequently used (Figure 10.104). Many companies produce special microchips that carry out functions of a monostable multivibrator. In powerful impulse devices in the electric power industry such high-sensitivity devices do not always work well, as they tend to pick-up under the external electromagnetic influences, and not from the input signals. In addition, such elements are not yet relays and additional circuits required: power supply, amplifying circuits, input and output devices. As far as is known to the author, there are still no universal pulse relays for high currents suitable for every such application available today in the market, therefore in each concrete case designers must invent, design, and develop such a relay in order to solve each specific problem.

The author solved one such problem when he developed a variant of the pulse relay for high currents (Figure 10.105). As a result, this very reliable relay, with a very low input resistance (that is, not sensitive to electromagnetic influences) was developed. This relay,

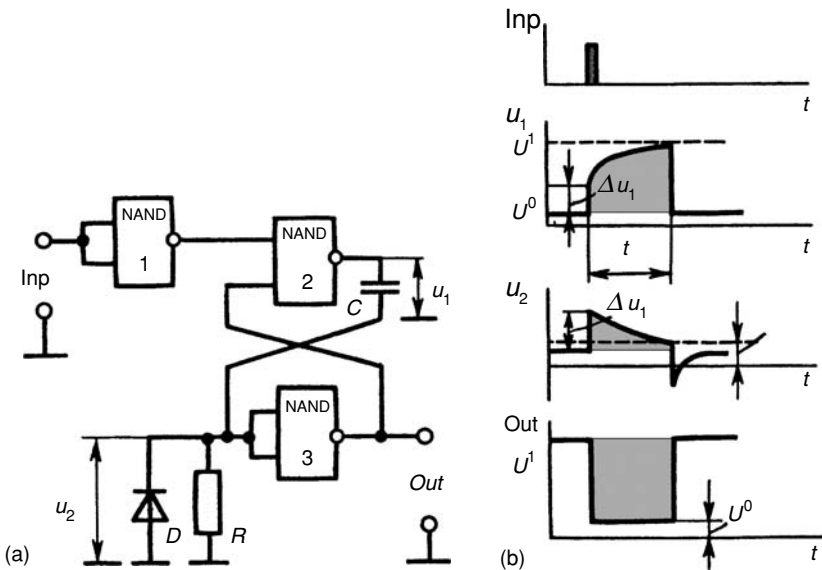


FIGURE 10.104
Univibrator: circuit diagram with NAND logical elements and oscillograms.

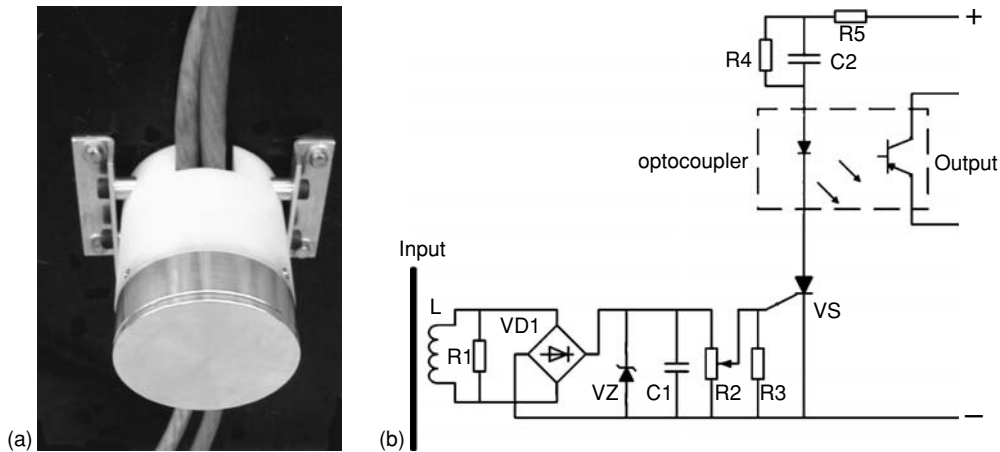


FIGURE 10.105
External view (a) and circuit diagram (b) of the pulse relay for high currents.

fixed on a thick copper conductor is capable of pick-ups from short pulses of current of only 5 to 10 μsec duration, with amplitudes from several tens of amperes up to several tens of thousands of amperes.

In tests, the high-voltage pulse generator of this relay made single current pulses with amplitudes ranging from 200 up to 20,000 A and standard pulse shape with $T_1/T_2 = 8/20$ (Figure 10.106). The exact threshold of the pick-up of this relay is adjusted by an internal trimmer. The duration of the output pulse depends on the capacity of capacitor C2 and can change from tens of milliseconds within a few seconds.

Three independent identical units were used in the specific design of the relay developed by the author, adjusted on three different thresholds of pick-ups: 300, 1000, and 10,000 A (Figure 10.107). Each unit contains a thyristor VS1, which will be actuated by input pulse with level, exceeded of preset (by trimmer R2) value and switched ON during few microseconds. Capacitor C2 start charging across the open thyristor. Thyristor remains in open state during capacitor charging time and turned OFF after capacitor C2 will be fully charged. In other words, weight of output pulse (up to 150 V, 0.1 A) is equivalent

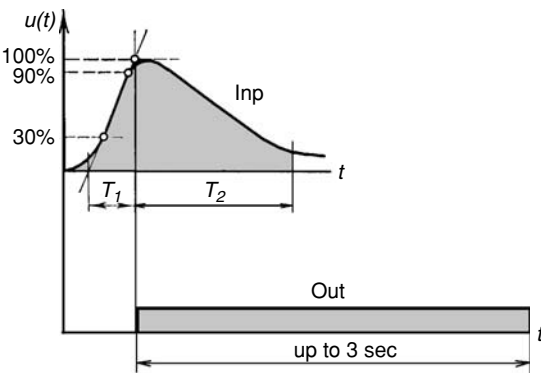


FIGURE 10.106
Input pulse shape applied to relay during test and signal on relay output ($T_1/T_2 = 8/20 \mu\text{sec}$).

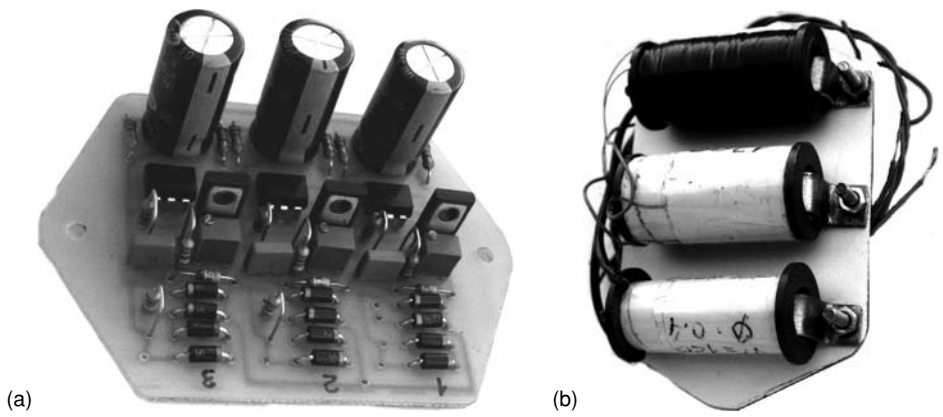


FIGURE 10.107
Printed circuit board (a) and input coils unit (b) of the multistage pulse current relay, developed by author.

to the capacitor time charging. Relay returns to its initial state after capacitor $C2$ will discharge across resistor $R4$.

If the printed circuit board and input coil are placed in a high-voltage insulating case (like that are used in high-voltage reed relays of the RG-series, described above) and filled with epoxy resin, the result will be a fine high-speed protective relay with high-voltage isolation.